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SEDIMENTARY PETROGRAPHY

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SEDIMENTARY PETROGRAPHY

*With Special Reference to Petrographic Methods of
Correlation of Strata, Petroleum Technology
and other Economic Applications
of Geology*

BY

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PREFACE TO THE THIRD EDITION (REPRINT)

The first edition of this book was published in August, 1922. It was designed to meet requirements of everyone then engaged in the study of microscopical examination of sediments—more especially incoherent detrital deposits—whether for academic or economic purpose. The plan adopted was much the same as that forming the basis of a course of lectures in Sedimentary Petrography (as applied to Oil Technology) given at that time by the author at the Royal School of Mines. It concerned the application of Sedimentary Petrography to certain branches of pure and economic geology, though no degree of finality was claimed to have been reached, it being well appreciated that a vast amount of research, both in the field and laboratory, awaited prosecution. It was the author's original aim to show how petrographic methods could be used as a means of correlating loose detrital sediments and to indicate the wider potentialities of the subject; in fact the book at this stage was intended to serve simply as a general introduction.

Meanwhile study of detrital minerals became more and more attractive by virtue of a wider appreciation of its application to petroleum geology and also its usefulness to a steadily increasing international body of students interested in its academic and economic possibilities. Indeed, accumulated data assumed such outsize proportions that it was decided to incorporate it in a Supplement rather than increase the original volume to twice its size and twice its price. In this way an opportunity was afforded to those possessing the original volume to bring it up to date, without repurchasing much of the original subject matter. The Supplement was duly published in 1926. It contained much that was new in technique and made known since 1922; additionally in the detrital range, twenty minerals were described and twenty-eight species figured, making in the two

companion volumes a total of more than 50 illustrations and 74 descriptions of distinct detrital minerals.

In 1927, the first edition of the Introduction was exhausted and reprinted in its original form.

The Second Edition of this work appeared in 1929. It embodied certain sections of the original (1922) volume, much of the Supplement (1926)—both subjected to critical revision—and a great deal of new matter. The blending of the data compelled entire rearrangement of text and its division into eleven chapters and three appendices. The aim was to bring the whole work up-to-date, to enlarge its scope, and provide a comprehensive text book of petrology of sediments, both incoherent and consolidated.

Apart from additions to the original text, several new chapters appeared in this edition. One concerned the microscope and its role in this particular research; another was devoted to quantitative aspects of the subject. Chief departure from original plan was the inclusion of a chapter on consolidated sedimentary rocks, embodying the cumulative evidence by which they could be classified and in thin section compared for correlation or differentiation in oilfield technology or other circumstances. Increasing activities of investigators of soils and related superficial deposits led to the inclusion of a chapter on the applications of sedimentary petrography to the rapidly widening science of pedology.

The Second Edition with its expansion of old material and new subject matter was bound in one volume, containing 514 pages of text, as opposed to a total of 281 pages in the Introduction and Supplement together. It was exhausted within six years.

Unavoidable delay and outbreak of the Second World War postponed publication of the Third Edition until 1940. In some ways this was an advantage as it afforded the author an opportunity to review over a decade of international reaction to a subject which by this time was well-established and popular. Substantial progress had been made in the science and art of studying sediments, more particularly their finer clay and soil components, by virtue of specialist X-ray, spectroscopic and base-exchange techniques. The demands of many industries

accelerated investigation of all sorts and conditions of sedimentary rocks, and the contemporary vogue for standardising raw materials and products hastened evolution of reliable methods of test, leading to accurate classification and maintenance of high quality status. Once again, therefore, it became necessary to revise and rewrite much of the existing (1929) text and to add as much new matter of pertinent aid in contemporary work as was available from centres of research and industry at home and abroad; also to eliminate methods of examination of sediments regarded as obsolete and superseded by better and more up-to-date technique.

The new edition, apart from additional data in the sections on descriptive mineralogy and petrology, included no less than six chapters covering mechanical analysis, mineral concentration, X-ray, spectrum, fluorescence, micro-chemical, microscopical and other methods of approach to practical problems presented by sedimentary raw materials. Apart from specialised application of the subject to stratigraphical correlation, more particularly in its bearing on petroleum technology, the new edition indicated its relevance to building and highway construction, forensic science, medicine and water supply. Modern applications in the asphalt, ceramic and refractories industries were also discussed.

To take care of all relevant material then available, the publishers decided on an important departure from procedure by making the edition demi 8vo instead of crown 8vo. The enlarged book contained about 680 pages and the number of illustrations, photomicrographs and line drawings was proportionately increased.

This is the edition which the publishers have no alternative but to reprint in its entirety, with a new Preface and Corrigenda, to meet long overdue orders and fill the gap until a Fourth, revised and up-to-date edition is available. This is already in preparation, but the wealth of new material must inevitably delay publication for some time to come.

The author is indebted to many friends who have helped him in preparation of this book, its revision and reprints, throughout the years, and desires to record once again his appreciation and gratitude to each and every one of them.

Unfortunately limited space now precludes adequate individual tributes.

In the early days of the Introduction, G. M. Part, M.A., A. Brammall, D.Sc., G. S. Sweeting, D.I.C., and the late H. H. Thomas, Sc.D., rendered invaluable assistance. The late G. H. Freeman (Murby) guided the book through the press with painstaking care. The Supplement had additionally the advantage of useful suggestions from F. T. Ingham, Ph.D.

The Second Edition benefited from the help of Mrs. C. Raeburn who undertook much of the proof reading. P. G. H. Boswell, F.R.S., apart from a critical reading of the text, made many helpful suggestions. J. N. Montgomery, M. H. Lowson and R. C. Jennings helped materially in checking mineral data and preparation of the bibliography. A. Brammall, G. S. Sweeting and the late G. H. Freeman again played an important part in the preparation of the new edition.

L. J. Chalk, M.Sc., F.R.I.C., at that time Chief Chemist, Geochemical Laboratories, was entirely responsible in the Third Edition for Chapter IV on Mechanical Analysis, for Chapter VI on X-Ray, Spectrum etc. Analysis, and for Chapter VIII on Methods of Testing Sedimentary Rocks. He also materially assisted in preparing data for Chapter XV on Applied Sedimentary Petrography.

Miss Doris Gray, B.A., then Secretary, now Partner, Geochemical Laboratories, undertook most of the bibliographical research necessary to bring the book up-to-date. She was responsible for adding to and rewriting much of Chapter XIV on Soils, for compilation of tables of mineral constants, bibliographies and indexes, also for proof reading.

F. Smithson, D.Sc., the well-known authority on detrital sediments, gave expert advice and practical assistance, more especially in preparation of mounts of a number of minerals and in the arduous task of proof-reading. The late G. H. Freeman (Murby) again lent his vast publishing experience to the author who freely acknowledges that much of the credit for this work since its inception in 1922 is due to that gentleman.

Acknowledgments are also due to the following for loan and permission to reproduce many rocks and mineral concentrates, micro-slides, photomicrographs, illustrations and blocks;

for preparation of new mounts, illustrations and line drawings; for permission to reproduce results of analyses made in the author's laboratories; and for all the many kindnesses shown during the thirty years of growth of this book. The list cannot inevitably embrace all who have helped, but it is the author's desire to thank again here each and every one who has assisted him.

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CONTENTS

	PAGE
PREFACE TO THE THIRD EDITION	v
CORRIGENDA	x
IMPORTANT NOTE	xi
CONTENTS	xiii
LIST OF FIGURES IN TEXT	xv
LIST OF PLATES	xvii
CHAPTER	
I. Introduction to the Study of Sedimentary Rocks ✓	1
II. Sampling of Sedimentary Rocks : Surface and Sub-surface Samples, Storage and Records	15
III. Laboratory Technique . .	31
IV. Laboratory Technique (<i>Continued</i>): Mechanical Analysis of Sediments .	82
V. Laboratory Technique (<i>Continued</i>): Further Methods of Mineral Concentration	121
VI. X-Ray, Spectrum, Fluorescence and Micro-Chemical Methods of Mineral Analysis	133
VII. Microscopical Examination of Sediments	152
VIII. Methods of Testing Sedimentary Rocks	191
IX. Diagnostic Properties of Sedimentary Rock Minerals	215
X. The Petrography of Consolidated Sediments	358
XI. The Principles and Practice of Differentiation and Correlation of Sediments by Petrographic Methods	431
XII. Some Examples of Differentiation and Correlation of Sediments by Petrographic Methods	478
XIII. The Bearing of Sedimentary Petrography on Palæogeographical Problems	490
XIV. The Application of Sedimentary Petrology to the Study of Soils and Related Superficial Deposits ✓	515
XV. Applied Sedimentary Petrology ;	536

APPENDIX	PAGE
I. Minerals arranged according to their systems of crystallisation	603
II. Amorphous Minerals	604
III. Minerals arranged in order of hardness (Mohs' scale)	605
IV. Minerals arranged in order of specific gravity	607
V. Minerals arranged according to their intermediate indices of refraction	611
VI. Isotropic Minerals	612
VII. Minerals arranged in order of birefringence	613
VIII. Minerals arranged in order of optical sign	614
BIBLIOGRAPHY	615
SUBJECT INDEX	639
AUTHOR INDEX	660

LIST OF FIGURES IN TEXT

FIG.		PAGE
1	Specimen Well-Sample Card	26
2	Sampling from Bulk—Quartering	28
3	Apparatus for Preparation of Synthetic Resin	45
4	Polarising Microscope	48
5	Bromoform Separation Apparatus for Single Samples	53
6	Funnel-battery for Bromoform Separation	64
7	Spaeth Sedimentation Glass	73
8	Use of Fused Salts in Mineral Separation	74
9	Graphical Method of Recording Results of Grading of Aggregate	93
10	Fineness Modulus	94
11	Single-Vessel Elutriator	97
12	Andrew's Kinetic Elutriator	99
13	Mayntz Petersen Fluorimeter	104
14	Pipette Apparatus	108
15	Weight Accumulation Curves	112
16	Horseshoe Magnet with Adjustable Pole Pieces	122
17	Electro-Magnet	123
18	X-Ray Spectrometer	136
19	Micro-Analytical Balance	148
20	Pregl Micro-Filtering Apparatus	149
21	Petrological Microscope	154
22	Stereoscopic Binocular Petrological Microscope	156
23	Intensity Lamp	159
24	Microscope Lamp	160
25	Dark Ground Illuminator	161
26	Auxiliary Micrometer Stage	162
27	Spectroscopic Eyepiece Attachment	163
28	Quartz Wedge	164
29	Becke's Line R.I. Test	167
30	Uniaxial Interference Figure	172
31	Biaxial Interference Figures. A. 90° Position; B. 22½° Position; C. 45° Position	173
32	Effects of Superimposing Quartz Wedge on Uniaxial Figures	174
33	Partially developed Uniaxial Interference Figure	175
34	Diagram of Optic Axial Plane etc.	176
35	A. Effect of Superimposing a Quartz Wedge on Biaxial Positive Interference Figure. B. Effect of Superimposing a Quartz Wedge on Biaxial Negative Interference Figure	177
36	Immersion Method of R.I. Determination	181
37	Method of Folding Filter Paper for Bitumen Extraction	194
38	I.P.T. Moisture Apparatus	199
39	McLeod Porosimeter	202
40	Vacuum Desiccator	206
41	Le Chatelier Flask	210

FIG.		PAGE
42-48	Crystal Forms of the Isometric System	217
49-54	" " " " Tetragonal System	218
55-60	" " " " Hexagonal System	219
61-67	" " " " Rhombohedral System	220
68-72	" " " " Orthorhombic System	221
73-75	" " " " Monoclinic System	222
76-77	" " " " Triclinic System	222
78	Interference Figure of Brookite (Dartmoor)	256
79	Dumortierite from Dartmoor Granite	279
80	Galena	286
81	Ilmenite	301
82	Kaolinite	303
83	Magnetite	310
84	Conglomerate (Hertfordshire " Pudding Stone ")	363
85	Breccia	364
86	Sandstone, Penrith, Cumberland	367
87	Grains from the Loess, China	381
88	Infusorial Earth, Richmond, Virginia, U.S.A.	404
89	Coal Constituents: clarain, durain, fusain, vitrain	410
90	Impregnated (Asphaltic) Limestone, Gard, France	416
91	Distributive Province Diagram	435
92	Vertical Sections and Mineral Zones	436
93	Current-Action on Deposition	438
94	Chart of Mineral Data	446-7
95	Graphical Method of Expressing Frequency	458
96	Persistence Diagram	462
97	Heavy Minerals and Unconformities	465
98	" " and Current-Bedding	467
99	Diagram to illustrate Transgression of Chronological and Lithological Planes	469
100	Soil—Relation to Bedrock	517

LIST OF PLATES

<i>Plate</i>		<i>facing page</i>
1	SHAPE OF PARTICLES A Angular B Subangular C. Rounded	117
2	HALLIMOND ELECTRO-MAGNETIC SEPARATOR FOR MINERAL POWDERS	124
3 A. B.	HILGER AUTOMATIC QUARTZ-GLASS SPECTROGRAPH HANOVIA-MUIR ANALYTIC LAMP FOR ULTRA-VIOLET FLUORESCENCE	145
4 A, B. C.	PLEOCHROISM Tourmaline and Dumortierite PARALLEL EXTINCTION Quartz 90° and 45° Positions	165
5	EFFECT OF POLARISED LIGHT A. Normal Transmitted Light B. Doubly Polarised Light	172
6 A. B-D.	ACTINOLITE ANATASE	229
7	ALMANDITE GARNET FROM DIFFERENT BRITISH STRATIGRAPHICAL HORIZONS	233
8 A. B.	ANDALUSITE ANDESINE	236
9	ANHYDRITE	240
10 A, B. C, D.	ANORTHOCLASE APATITE	241
11 A. B, C.	ARAGONITE AUGITE	245
12 A. B, C. D.	AXINITE BARITE BIOTITE	252
13	BROOKITE	256
14 A-C. D-F.	CALCITE CASSITERITE	257
15 A. B, C. D-F.	CEYLONITE CHERT CHIASTOLITE	261
16 A, B. C. D.	CHLORITOID CHRYSTOLE CORDIERITE	268
17 A. B. C, D. E.	CORUNDUM DIOPSIDE DOLOMITE DUMORTIERITE	272
18 A, B. C, D.	ENSTATITE EPIDOTE	281

<i>Plate</i>		<i>Facing page</i>
19	A, B. FLUORITE	288
	C. GLAUCONITE	
20	A, B. GYPSUM	297
	C. GLAUCOPHANE AND HORNELENDE	
	D. HYPERSTHENE	
21	A. KYANITE	309
	B. LEUCOXENE	
	C, D. LIMONITE	
22	MONAZITE	314
23	A, B. MICROCLINE	316
	C, D. MUSCOVITE	
24	A, B. OLIVINE	325
	C, D. PYRITE	
25	QUARTZ	332
26	A, B. RUTILE	337
	C. SPHERULITIC SIDERITE	
	D. SILLIMANITE	
27	A, B. SPHALERITE	338
	C. SPINEL	
	D. SPODUMENE	
28	A, B. STAUROLITE	341
	C, D. TITANITE	
29	A. TOPAZ	348
	B. TOURMALINE	
30	A. TREMOLITE	352
	B. WOLLASTONITE	
	C. ZOISITE	
31	ZIRCON	353
32	SANDSTONE AND GRIT	368
33	ARKOSE, QUARTZITE AND GREYWACKE	372
34	CLAY, MUDSTONE AND SHALE	381
35	MARL AND LIMESTONE	388
36	LIMESTONE AND DOLOMITIC LIMESTONE	392
37	DOLOMITIC, OOLITIC AND PISOLITIC LIMESTONES, OOZE AND CHALK	397
38	CHEST, FLINT, SILICEOUS OOZE AND DIATOMITE	401
39	LIGNITE AND COAL	404
40	OIL SHALE	413
41	ASPHALT AND BITUMEN-IMPREGNATED ROCKS	416
42	PHOSPHATES AND BEDDED IRON ORES	421
43	CHLORIDE AND SULPHATE	428
44	SULPHATE AND NITRATE	430
45	HEAVY MINERAL RESIDUES FROM OIL SANDS IN CALI- FORNIA AND RUMANIA	479
46	HEAVY MINERAL RESIDUES FROM TERTIARY ROCKS, RUMANIA	482
47	HEAVY MINERAL RESIDUE, WEALDEN (LOWER CRETACE- OUS), S.E. ENGLAND	485
48	AGGREGATES FROM VARIOUS ASPHALTIC LIMESTONES	541
	A. Boeton, Dutch East Indies	
	B. Scafa, Italy	
	C. Sicily	
	D. St. Jean de Maruéjols, Gard, France	
	E. Pyrimont, Seyssel, France	
	F. Val de Travers, Neuchatel, Switzerland	

LIST OF PLATES

xix

49	ASPHALTIC LIMESTONES (NATURAL ROCK ASPHALTS)	
	A. Boeton, Dutch East Indies	} 542
	B. Scafa, Italy	
	C. Sicily	
50	ASPHALTIC LIMESTONES (NATURAL ROCK ASPHALTS)	
	A. St. Jean de Maruéjols, Gard, France	} 544
	B. Montrotier, Seyssel, France	
	C. Pyrimont, Seyssel, France	
51	ASPHALTIC LIMESTONES (NATURAL ROCK ASPHALTS)	
	A. Val de Travers, Neuchatel, Switzerland	} 546
	B. Vorwohle, Hanover, Germany	
	C. Natural Rock Asphalt Powder contaminated with British Carboniferous Limestone	
52	A, B. RAW MATERIALS FOR REFRACTORIES	
	A. Magnesite, Salzburg, Austria	} 589
	B. Sillimanite, India	
	C-F. REFRACTORY PRODUCTS	
	C. Siliceous Brick	
	D. Silica Brick	
	E. Silica Brick	
	F. Cristobalite and Tridymite	

CHAPTER I.

INTRODUCTION TO THE STUDY OF SEDIMENTARY ROCKS.

SEDIMENTARY rocks include all consolidated and incoherent sediments composing the earth's crust, irrespective of their mode of origin, *other* than those rocks formed directly by igneous activity; they thus embrace rocks of mechanical, organic and chemical origins and characteristics.¹

The petrology of sedimentary rocks implies their comprehensive study by relevant chemical, geological and physical methods, both in the field and in the laboratory, leading to an understanding of their natural history, in so far as such study may guide its interpretation.

Sedimentary petrography may be defined as the systematic description of sediments, implying their lithology and mineralogy and, in a wider sense, their genesis. Lithology means determination of rock characteristics in the mass *in situ* as well as in representative samples in the laboratory. The mineralogy of sediments implies detailed chemical and physical determinations, either on the natural raw materials, in thin sections or on specially prepared mineral grain segregations.

Since the beginning of the present century conventional treatment of the petrology of sedimentary rocks has tended to emulate that of igneous rocks in so far as keeping a reasonable balance between petrography and petrogenesis is concerned, though the latter term is seldom, if ever, used in connexion with origin and mode of formation of sediments. Be that as it may, modern intensive studies of these rocks have expanded this branch of geological science into another and not less effi-

¹ Pyroclastic rocks, *i.e.* fragmental products of explosive volcanic action, when deposited under water frequently become admixed with ordinary sedimentary detritus; they may thus exhibit stratification and sometimes contain fossils. These rocks, however, constitute a special case falling by affinities with volcanic rocks more naturally within the domain of igneous petrology; their consideration is consequently omitted from this book.

cient "handmaiden" to stratigraphy, while their influence in the philosophies of palæogeography has been by no means unimportant.

This petrology, however, for long lacked both student and status in Britain compared with its sister science of igneous rocks. A curious apathy to study sediments for their own sake pervaded spheres of geological learning well beyond the beginning of the present century; a consequent dearth of fundamental information on British sediments was only really made good as a result of economic exigencies of the Great War (1914-18).

Prior to this, contributions to our knowledge of these rocks were, if outstanding, none the less sporadic. In the academic world, sediments were fortunate if they received brief treatment and speedy dismissal at the closing stages of full courses in igneous petrology. In the realm of stratigraphy, it was field relationships and fossils that gave individuality to these rocks, not their inherent composition and provenance. So has it been generally in petrological research, where for every one pioneer in studies of sediments, igneous petrology could claim a score. All that is now altered and the work of over two decades, both in Britain and abroad, has brought this branch of natural science into the forefront of both academic and economic geological thought wherever sediments are involved.

To what extent the "heavy mineral" cult was responsible for awakening long-delayed interest in sedimentary rocks may be debatable, but it is none the less a claim with some foundation. Constant repetition of sedimentary rock types as studied in thin section might perhaps be an excuse for general lack of interest in them, but an ever-changing galaxy of mineral grains, once their broader significance was appreciated, could not do other than revive this interest and stimulate research anew.

On the purely academic side, the tendency was at first towards study of the subject for its own sake, with little or no regard for its broader possibilities; the sampling of a particular sediment, the segregation of its "heavier" and more stable constituents and their ultimate mineralogical analysis, formed a welcome change from the routine investigation of thin sections of consolidated rocks and one which was followed mainly because it was, indeed, a new departure in experimental petrology. This narrowness of treatment, however, was destined to be

rapidly transgressed and one by one investigators became imbued with the broader potentialities of the subject, when it was realised to what extent fundamental problems in stratigraphical geology were capable of solution along these lines. Questions concerning the genesis of a sediment, involving not only ideas as to its source of origin but also definite conceptions of its mode of transport and deposition, the nature of environmental and climatic conditions at the epoch of its formation—together with the pertinent aid which the subject affords to palæogeographical restoration—are all embraced by systematic petrographic examination of a series of deposits. It is not difficult, therefore, to appreciate the reasons underlying the rapid evolution which has taken place since that war of a technique offering so many far-reaching possibilities.

Apart from these more academic motives, that war period provided an impetus to research on sediments such as had never before been undertaken either in Britain or elsewhere. An urgent necessity to utilise national resources of sediments of one kind or another to replace former foreign supplies initiated (chiefly under the aegis of the then Ministry of Munitions) extensive investigations into sands, clays and other sediments; this work was not only fundamental from an economic standpoint, but both then and subsequently exerted considerable influence in establishing the science on a firm modern basis. With research on sands suitable for glass-making, foundry work and other purposes, the name of P. G. H. Boswell is closely linked. Contemporary investigations by officers of H.M. Geological Survey into the mineral resources of Great Britain provided much new data on sedimentary rocks such as ganister, silica rock, fireclay, dolomite, oil shale, lignite, cannel coal, bedded iron ores, rock salt deposits etc., with petrographical and chemical data on certain of these types which have proved an invaluable guide in subsequent work on these materials.

In another direction sediments were being attacked from an entirely different angle. The rapid development of petroleum geology during this same period and the problems besetting subsurface identification and correlation of often unfossiliferous strata penetrated by the drill, led to consideration of possibilities of petrographic methods in this connexion.

In Trinidad in 1915 and subsequently, V. C. Illing clearly demonstrated the great value attaching to a detailed petrological study of the highly disturbed oil-bearing strata in the southern part of that island. His recognition of successive groups of sediments characterised by exclusive heavy mineral assemblages constituted a new weapon of attack on problems of differentiation and correlation of strata which had previously defied solution. Thus was laid the foundation of this particular application of petrographic methods to stratigraphical analysis—one destined to aid substantially investigations of oilfield sediments in other countries as well as detrital deposits at home and elsewhere.

At this point it is convenient to take stock of British pioneer work on sediments from the time when H. C. Sorby first described his work on "The Structure and Origin of Limestones" (1879) and on "The Structure and Origin of Non-Calcareous Stratified Rocks" (1880), in two dissertations which undoubtedly laid the foundations of the technique of study of sedimentary, as distinct from igneous, rocks. Admittedly, other workers before him, both in this country and abroad, contributed descriptions of sediments in which some measure of mineralogy was foremost, but the literature has to be critically searched for past efforts which have "lived" to be still in any sense terms of reference, and no useful purpose would be served here in listing every contribution.

A frequently quoted first paper in the realm of heavy mineral investigation is that of A. Dick, who recorded his observations *inter alia* on the Bagshot Sands of Hampstead, London, in 1887; this brief contribution to "Nature" apparently did not excite the imagination it might have been expected to do among contemporary petrologists, but it has become a minor classic of its kind in the annals of sedimentary petrography. In the same year a paper by J. J. H. Teall describing the occurrence of rutile needles in certain clays showed that the author of "British Petrography" (1888) was fully alive to possibilities of intensive investigation of constituents of the finer grained sediments, even though his *magnum opus*, save for one illustration, contained nothing at all on sedimentary rocks.

W. M. Hutchings' essays on detrital minerals of clays and slates (1890, 1894) demonstrated still further what could be done by painstaking analysis of fine-grained sediments; these papers are still often referred to in contemporary writings. Then came W. Mackie; his published work, from an early account of the "Sands and Sandstones of Eastern Moray" (1896), followed in 1897 by consideration of the mechanism of rounding of sand grains (a fitting prelude to modern research on shape and size of incoherent rock and particles), then later by his detailed studies of "Purple Zircons in the Sedimentary Rocks of Scotland" (1923), "Apatites" (1926), to "Heavy Minerals in the Torridon Sandstones" etc. (1928), has invariably borne the stamp of originality of design and interpretation.

The year 1900 saw the publication of T. G. Bonney's researches into the Bunter Pebble Beds of the Midlands, in which he dealt with their petrography, mode of transport and possible source of origin. Though dealing essentially with pebbles and boulders, the principles he so well demonstrated clearly established a basis of parallel reasoning in the natural history of finer material; shortly afterwards (1902) there appeared an outstanding paper by H. H. Thomas on "The Mineralogical Constitution of the Finer Material of the Bunter Pebble Bed in the West of England," a model of mineralogical accuracy and palæogeographical vision which undoubtedly revolutionised work on sedimentary deposits of this kind; this paper was followed in 1909 by a similar contribution on "The Petrography of the New Red Sandstone in the West of England," in which H. H. Thomas again made evident the vital importance of precision in mineral grain determination, the significance of provenance and the stratigraphical value of these inorganic indices of past events. Many publications by others of a similar character have since appeared, but each inevitably bears tacit, if not actual, acknowledgment of the teachings of a great petrographer. Attention may conveniently be drawn at this stage to two essays of outstanding merit which should be carefully read by all students of sedimentary petrology in its broadest applications; both are presidential addresses delivered to the Geological Society of London, one

by J. E. Marr in 1905 on "Classification of Sediments," the other by W. W. Watts in 1911 on "Geology as Geographical Evolution."

In the former paper an analogy was drawn between meteorograms, as recording meteorological variations, and "geograms," a word used by J. E. Marr in place of the expression "Geological Column" and connoting principally variations in lithology and in organic assemblages that could be traced in a deposit, if a column obtainable from boring right through it were laid flat and studied from one end to the other. Although purely a hypothetical conception, the "geogram" is the ideal to which all petrographic investigations should tend and even though the tracings are broken or discordant, as they are bound to be, the evidence will be none the less valuable and suggestive.

W. W. Watts enlarged this conception in the following words:—"In order to obtain what Dr. Marr has called the 'geogram' of a formation in its greatest perfection, we require to know the entire extent of its variations, not only along its outcrop, but in that part which is hidden from sight; and we ought to be in a position to infer the probable variations in that almost equally important part which has been destroyed by denudation."

The few years preceding 1914-18 were not conspicuous for prolific publication on sediments, but research was none the less active; H. H. Thomas continued his descriptive work on varied West of England deposits; T. Crook dealt with technique (1908-09) and also gave the first systematic account of the then-known commoner detrital minerals in an appendix to F. H. Hatch's "Petrology of Sedimentary Rocks" (1913); G. M. Davies published (1912) the first of a series of useful papers on the mineralogy of different sediments in London and the Home Counties; R. H. Rastall devoted much attention to technique and to the mineralogy of Cambridgeshire sands and gravels (1913).

Then came the war period when research was intensified, though essentially economic in bias and the work of P. G. H. Boswell and V. C. Illing in the special fields already mentioned (p. 3, 4) are the clearest land-marks. To appreciate the

advances made at this time, both in technique and outlook in this subject, the reader is referred to a suggestive article on "The Application of Petrological and Quantitative Methods to Stratigraphy" by P. G. H. Boswell (1916), which in point of fact gave a succinct account of the methods whereby J. E. Marr's "geogram" might best be attained; this essay presented valuable co-ordination of facts and constructive criticism of hypotheses then current.

With the post-war period came a flood-tide of enthusiasm for sedimentary petrology in this country and both in teaching and research great energy was devoted to the subject in practically every centre of learning; the number of workers in the field thus rapidly increased. At this time much original work on Yorkshire sediments appeared, culminating in an inspiring account of the Millstone Grit from the pen of A. Gilligan (1920).

The author's own researches on correlation of isolated Tertiary deposits in Western Cornwall (1922), on Wealden sediments (1922-25) and on well samples from oil fields in different parts of the world aided development of technique of differentiation and correlation of sediments and served to sustain the validity and value of petrographic methods applied to stratigraphical and structural problems.

A further application of the subject to alluvial mining was indicated by the author in a paper published in 1923¹ and has since been made the theme of a separate exposition in conjunction with C. Raeburn.² This phase of "Sedimentary Mineralogy," as it has been aptly termed by A. Holmes, is both in principle and practice but a logical outcome of comprehensive study of sediments, whether recent or ancient; the particular technique implied has since influenced developments of alluvial mineral deposits in different parts of the world. Quite apart from an economic bearing, investigation of alluvial "heavy" minerals is of the greatest possible value—incidentally a most fascinating pursuit—in all problems of detrital mineralogy.

The period 1922 to date witnessed remarkable expansion in the study of sedimentary rocks, consistent with the many

¹ H. B. Milner, *Min. Magazine*, 28, 1923, p. 80.

² "Alluvial Prospecting." Murby, London, 1927.

newcomers in this field. Specific mention must be made of a series of highly original papers by A. Brammall and H. F. Harwood on the Dartmoor Granite, giving results of detailed geochemical and petrological observations profoundly affecting conceptions of provenance and significance of sedimentary rock minerals, quite apart from the direct influence of this work in the domain of igneous petrology. These authors firmly established a technique (it was initiated on a smaller scale by R. H. Rastall and W. H. Wilcockson in 1917 in their investigation of certain Lake District granites), involving isolation and intensive study of accessory minerals in igneous rocks, since become the pattern of a large volume of similar work both at home and abroad.

The work of S. W. Wooldridge on the "Bagshot Beds of Essex" (1924) and on "The Pliocene History of the London Basin" (1927) is distinctive for its originality of thought and interpretation in deciphering the natural history of the rocks of this part of England; equally W. F. Fleet's minutely detailed contributions to our knowledge of Palæozoic sediments in the Midlands (1923-33); again, F. Smithson's descriptive work on accessory minerals of certain Irish granites (1928), his careful enquiries and deductions on frequency estimations of heavy mineral suites (1930) and his later work on "The Triassic Sandstones of Yorkshire and Durham" (1931) are each noteworthy contributions to the subject. I. S. Double (1924-31) contributed various papers on the petrography of sediments, characterised by careful attention to detail of mineral constitution, while these same petrographic methods have been vigorously and successfully employed by J. D. Solomon in his studies of glacial deposits of East Anglia (1932).

Contributions to the science from the scattered countries of the British Empire are by no means insignificant, even if less well known. Much useful work of wider application perforce lies hidden in various official publications, such as those of state geological surveys. Apart from general stratigraphical descriptions, such mineralogical bias as may be afforded sediments frequently tends towards material of economic value, *e.g.* alluvial deposits, but it is none the less interesting on that account. The Canadian and Indian Geological Survey pub-

lications, to cite only two examples, are frequent sources of much more than parochial information on sediments, while the *Bulletin of the Imperial Institute* provides a regular survey of discovery, research and bibliography which brings all important colonial work within easy and constant reach of the student of sedimentary petrology.

Turning now to Europe, excluding the British Isles, the early history of sedimentary petrology appears conspicuously bound up with design of methods and materials for studying incoherent rock minerals and in this connexion the names of certain mineralogists stand pre-eminent in the records. As in Britain, applications of petrographic methods to stratigraphy did not come until much later and even now in some countries they have been hailed as quite a modern innovation. Space precludes survey of every continental field of activity, but the following review will serve to convey some idea of the more important past and contemporary work in this science which may justly be said to have had international influence.

In Belgium, there is J. Anten, whose work has chiefly concerned examination of heavy minerals of various sands in that country (1919-28); also A. Doyen's researches of a like character (1923-27).

In France, L. Cayeux is probably best known for his "Introduction à l'étude pétrographique des Roches Sédimentaires" (1916 and 1931), an invaluable guide to mineral diagnosis; his "Les Roches sédimentaires de France (Roches siliceuses)" (1929) is an authoritative account of varied types of sedimentary siliceous rocks. A. F. A. Lacroix' contributions to the rare-earth bearing sands of Madagascar are well known and, to a lesser extent perhaps, J. de Lapparent's petrographic studies of felspar in sediments (1918). The name of J. Thoulet is outstanding as an indefatigable investigator for over fifty years of all kinds of incoherent deposits, recent and otherwise, also particularly for his inventive ability in establishing technique of manipulating these materials. A more recent contributor, L. Berthois (1928-30), has studied the mineral composition of residual, decomposed igneous material in Brittany with interesting results.

Research on sediments has only in comparatively recent

years become popular in Germany and at the present time it is being pursued keenly by many workers. H. Becker in his reports to the Committee on Sedimentation (U.S.A.) shows that since 1930, at all events, contributions on practically every phase of the subject have been many; in point of fact the influence of American as well as British schools of thought at this time is clear. Investigations include principles of sedimentation, work on heavy minerals, products of sedimentation, structures of sediments, environment etc. On the purely practical side (heavy minerals), the names of H. Müller and W. G. Simon appear foremost, while sandstones have been specially studied by H. Klähn and others, clays by F. E. Klingner, calcareous rocks by J. Pia, H. Udluft and others, bituminous rocks by R. Potonié, O. Stutzer and W. Wetzel.

In Holland, the work of J. W. Retgers during the last two decades of the nineteenth century, especially on the dune sands of Sheveningen, is widely known and often quoted in subsequent literature. A more recent investigator, chiefly on petrology of soils of the Dutch East Indies, is J. van Baren (1922-30), whose work is a monument of detail and critical mineralogical observation. The work of C. A. Edelman is similarly well known.

The Italian school has long been prominent for publications on the petrography of recent sands from shore, river, lake and dune. In this connexion the name of E. Artini is associated with some minutely detailed studies in this field; I. Chelussi followed much the same technique with older consolidated rocks; E. Clerici is distinguished principally for mechanism of examination of minerals and for certain specifications of "heavy" liquids, one of which bears his name; F. Salmoiraghi worked in the early years of the present century on both recent terrestrial and marine sediments, also others of geological age, in detailed studies of their petrology.

The names of L. W. Collet and L. Déverin are noteworthy in the annals of Swiss researches on sediments, the former particularly for studies of lake deposits (1929), the latter for petrological investigations of Tertiary and Cretaceous sediments in that country (1924-25). E. Paréjas (1929) is also associated with the Geneva studies of lake deposits and has,

with Collet, rendered valued service to the Committee on Sedimentation (U.S.A.) in connexion with published bibliography of West European research on sediments (1930-31), of great use to English-speaking students.

In the United States the history of "sedimentation"—a convenient though much abused term—is remarkable for a rapidity of development and co-ordination of research which only a country with an innate flair for organisation could sponsor. While it may be argued that directed team-work in science tends to stifle individual initiative, there is no doubt that the output of newly acquired knowledge since sedimentation and sedimentary rocks became a "National Research" subject has been as surprising as it has proved welcome to students all over the world.

A pioneer in modern interpretation of the science was undoubtedly M. I. Goldman who published petrographies of the Catahoula Sandstone of Texas (1915), of Upper Cretaceous sediments of Maryland (1916), and later an exposition of Salt Dome Cap Rock (1925). Other prominent contemporary American investigators ("sedimentationists") include E. Antevs, E. Blackwelder, K. Bryan, M. A. Hanna, M. M. Leighton, F. J. Pettijohn, A. M. Piper, R. D. Reed, C. S. Ross, G. Steiger, W. A. Tarr, P. D. Trask, W. H. Twenhofel, T. W. Vaughan and C. K. Wentworth. Each of these geologists has during the last decade made substantial contributions to all branches of the subject which fall within the purview of the Committee on Sedimentation of the National Research Council; as periodical reports of the Committee have shown, this purview is a particularly comprehensive one and by no means merely national in outlook. Of special note is the "Treatise on Sedimentation" by W. H. Twenhofel (1926 and 1932), a monument of compilation of authoritative data and a basic volume to which every student of the subject must inevitably turn for enunciation of first principles.

To the United States is due the credit for producing the first periodical exclusively devoted to the study of sedimentary rocks. The *Journal of Sedimentary Petrology* (the first issue appeared in 1931) was an outcome of one phase of the literary

activities of the Society of Economic Palaeontologists and Mineralogists, a branch of the American Association of Petroleum Geologists, organised in 1927. Constant reference to this excellent journal and to papers emanating from the above-mentioned investigators will be found throughout this volume.

This brief sketch of progress in sedimentary petrology, though inadequate to portray a true picture of the remarkable advances made in the subject during recent years, will none the less serve to give the student an impression of the essentially international character of the science before him. Should he wish to probe more deeply into the purely historical side of investigations, P. G. H. Boswell's essays and bibliography "On the Mineralogy of Sedimentary Rocks" (1933) will be his best guide, while for contemporary work, the *Journal of Sedimentary Petrology* and the *Reports of the Committee on Sedimentation*, already referred to, will be found abundant and lucrative sources of newly acquired knowledge.

Apart from this, the foregoing résumé of men and work in sedimentary petrology necessarily omits account of a vast amount of unpublished work done in many of its economic applications, e.g. oilfield (subsurface) geology, refractories research, asphalt technology. With many industrial undertakings investigations into natural raw materials for building up new products have of necessity to be maintained under cloak of secrecy and much new data is thus lost to wider interests, at all events until such time as it is considered politic to make them known.

In the more direct applications to oil geology, there can in these enlightened days of co-operative development be little point in concealing results of intensive petrological or palaeontological research; in this connexion it is welcome to note that latterly artificial barriers of confidential (?) heavy mineral and/or micro-organic data have with most oil companies been broken down; general executive recognition has at last been given to the fact that individual company interests are best served by pooling scientific information of a critical or difficult stratigraphy wherever possible and practicable; that, after all, is in keeping with the highest traditions of advancement of natural science.

The debt which industry owes to science is constantly stressed in contemporary speech and writings. There is equally the other side of the story, the progress in academic thought and activity for which industrial demands are directly or indirectly responsible. With geology and particularly sedimentary petrology, the obligation to economics is real and should be properly acclaimed. In his report to the Committee on Sedimentation in 1934, the author wrote: "I am convinced from long experience that the greatest and most speedy evolution of knowledge of our subject can only be anticipated from recognition of its actual and potential services to the community. Descriptive stratigraphy has its place in academic knowledge, and it is proper that it should always maintain this place, that it should be studied impartially with no material aim other than to confirm or establish new principles on which geological science rests. Such description, to whatever detail it may go in the matter of component sediments, does, unless carefully watched, tend to become a matter of monotonous repetition; the monotony is immediately broken, however, by discovery of something hitherto unknown, by assemblage of facts leading to new trains of thought and activity and when, as a result of broader investigation, the data are capable of influencing some aspect of everyday life. I firmly believe that just as a community comes gradually to accommodate itself to new conditions and values of life, so in outlook must the geologist, in particular the sedimentary petrologist, shift his attitude to the science and hence make his work for it more in accord with the demands of the times."

That is equally true to-day. Each year witnesses an increase in the number of adherents to this branch of geology from all seats of learning throughout the continents of the world. Encouraging as this is, the student should approach his work with the twofold goal in view, that of advancement of geological knowledge and of making that knowledge available for the common good wherever its practical application may find outlet.

There is just one danger to be guarded against; that, notwithstanding many and varied expositions of first principles, purely analytical phases of the subject as treated here may

assume prominence out of all proportion to their actual worth; it is useless amassing quantities of facts without seeking to reconcile them with hypotheses capable of explaining their significance, thus contributing to the development of the science; if theory lags behind practice, the result must inevitably be to retard rather than to advance evolution of knowledge, no matter what branch of natural science is involved.

It is therefore necessary at the outset to stress the importance of the more fundamental aspects of sedimentary petrology, in particular the influence that its study must have on the progress of geological and industrial geological research. The fact that a large part of this book is concerned with descriptive mineralogy, petrology and laboratory technique should in no way cloud the true perspective of the subject; the determination of the mineral constitution of sediments is but a means to an end; it is the first stage towards unravelling their history, and getting to know everything there is to be learnt about them.

CHAPTER II.

SAMPLING OF SEDIMENTARY ROCKS : SURFACE AND SUBSURFACE SAMPLES, STORAGE AND RECORDS.

Sampling (General)—Auger-Drill Samples—Bit-Samples—Bailer Samples (Cable-Tool System)—Core-Samples—Fauck System Samples—Diamond Drill Cores—Containers—Labelling of Samples—Storage—Key-Samples—Sample Indexing—Sampling from Bulk for Laboratory Analysis—"Quartering."

Sampling (General). — Comprehensive sampling of a given sediment is at the outset a matter of great importance and one requiring systematic practice and care. Extensive deposits in the field can only be sampled satisfactorily providing there are numerous natural and artificial exposures accessible; this will obviously vary with the nature of the country in which investigations are being carried out.

Surface sampling, as distinct from subsurface sampling, should be effected at chosen intervals along and transverse to the strike of the beds, such intervals depending on the extent of the deposit, persistency of lithological facies and topographical and structural considerations. Sampling in vertical sections exposed by quarries, cuttings etc., involves collecting material from horizons determined primarily by change of lithologic facies and of texture of the rock. Where vertical sections are absent, samples collected superficially (unless the beds possess a marked regional dip) can only represent a very average composition of the horizon outcropping and will in themselves be little criterion of the nature of the concealed beds; under such conditions "pitting" may be necessary for the production of samples within 20 ft. of the surface. depending on local conditions, or failing that, a portable boring apparatus must be employed (see under *Auger-Drill Samples*, p. 17).

For sampling in depth (over 25 ft.), the geologist has to rely entirely on material taken from borings (oil, water etc.),

and the efficacy of such sampling will depend largely upon the system of drilling employed. Abrasive methods normally yield core-samples and these are the most valuable and easiest to deal with from the geological standpoint. Percussion methods using the "chisel" (cable-tool system) are specially adapted to oilfield and water-boring requirements and sampling, by means of a bailer or "shell," can usually be carried out. Samples thus obtained, however, are "cuttings" or comminuted rock, often unreliable as to precise horizon and actual lithology. The rotary system of drilling (now widely adopted) unfortunately precludes all chance of obtaining uncontaminated samples from washings in the "ditch," notwithstanding frequent assertions to the contrary, though the much greater use now made of core-drilling has gone far to obviate this disadvantage (p. 19).

Samples of incoherent material, such as sand, can most conveniently be collected in the field in numbered canvas bags (convenient size 9 by 6 in. with tapes to tie), each capable of holding about 1,500 gm. of material. Care should be taken to record the bag number, precise locality and horizon from which the sample is taken, both in a separate note-book and on a paper slip inserted in the bag. In collecting from a given exposure as, for instance, from a bed of sand 3 ft. in thickness, and in order to obtain as representative a sample as possible from this bed, the bag should be held open against the face and at the bottom of the bed and a geological hammer used to remove material by drawing it from the top of the bed downwards, the dislodged sand thus falling into the bag. Where there are several feet of rock exposed, this method can be repeated from one horizon to another, providing the whole section is accessible.

Surface sampling involves in each instance the taking of adequate amounts of material from proximate points to make up one sample which will be representative of the particular locality chosen, providing some degree of homogeneity of deposit is in evidence; rapid lateral variation will necessarily narrow down the limits within which this form of sampling may safely be employed.

Plastic rocks, such as clays, obviously do not lend themselves to the foregoing methods of sampling, the material

usually having to be cut out with a knife. It should be borne in mind that much larger samples of clay are required for proportionate yield of heavy minerals than in the case of sand; also that *the coarser the sand, the larger the sample necessary*, if a reasonable yield of mineral residue is sought.

Consolidated sediments, *e.g.* sandstone, shale, limestone, as is the case with igneous and metamorphic rocks, must be hammered out in the usual way, the material being subsequently crushed if the accessory detrital minerals are required.

Take care always to obtain unweathered samples.

Auger-Drill Samples.—During the course of geological field-work, where information is sought in critical places concerning the solid rock beneath sub-soil or alluvium, some device for procuring rapidly the desired samples has long been in request. In the early days of Wealden geology, the officers of the Geological Survey used to arm themselves with an instrument akin to a "cheesetaster" (as it was called), with which subsurface evidence was often quite satisfactorily obtained. From time to time various hand-drilling instruments have been used for a similar purpose, as for example, those described by A. C. Veatch in connexion with hydrological surveys in Louisiana.¹ It remained for V. C. Illing to introduce and develop the use of the modern auger-drill in Trinidad and the simplicity and efficiency of this instrument—simply a carpenter's auger attached to a suitable length of gas-pipe provided with a T-piece and rod for turning—has made it a most popular method of obtaining shallow subsurface samples of soft rocks such as clay, sand, silt, marl etc. Its use is not practicable with hard rocks or with coarse, loosely consolidated materials such as flint-gravel. Holes up to 20 ft. or more are possible by hand-turning alone, depending on the nature of the rocks traversed; the use of a tripod and winch with suitable pulley to aid in hoisting the pipe out of the hole enables far deeper borings to be made successfully.

The samples obtained by the auger-drill are those which are held in place in the convolutions of the bit to which they will readily adhere, especially if the sediment is a little moist; if drilling through dry, loose sand, a slight water-flush will

¹ "Water Resources in N. Louisiana" etc., *U.S. Geol. Surv., Prof. Paper* 46, 1906, p. 93.

supply the necessary amount of "bind." The sample clinging to the bit should, while still attached, be pared of its outer surface with a knife or suitable scraper, as the superficial material is liable to contamination from the sides of the hole as the bit is withdrawn; it is then recovered in the form of a "spiral" by running the finger from the cutting point of the bit upwards round the grooves, or alternatively, holding the bottom end of the bit between thumb and finger of the left hand and turning the bit itself in a clockwise direction with the right hand. Exceptionally clean samples, which are invaluable, not only for petrographic purposes, but for checking concealed rocks during the course of field-mapping, can be obtained in this way.

Samples thus obtained may be segregated in canvas bags (as above) and thus suitably transported, or an oilfield sample-container (p. 22) can be employed.

Bit-Samples.—So-called "bit-samples" or "drill-cuttings," *i.e.* rock-fragments clinging to the bit of a rotary- or cable-tool and thus recovered, must generally be regarded with suspicion. not only of possible contamination, but often of precise position whence derived; in the absence of other means for taking samples, however, such "cuttings" must often suffice; they are certainly better than nothing at all. Bit-samples obtained from a rotary-bit are invariably contaminated with mud; those obtained from a cable-tool bit are perhaps more reliable since they are less prone to that particular influence. With samples of this description, a great deal depends upon the type of bit employed, the efficiency of the driller and the care with which the cuttings are selected, preferably by the geologist.

Bailer Samples (Cable-Tool System).—These "cuttings" are frequently all that are available as a record of the rocks penetrated and, in the absence of caving strata or drilling mud, are generally uncontaminated; their reliability as a true index to lithology and horizon is, however, often a matter of doubt. The cable-tool system being usually employed for hard rocks, especially limestone, results in the bailer or "shell" yielding small fragmental samples normally, however, of sufficient size for subsequent production of thin sections.

To a large extent the disadvantages of bailer "cuttings" are overcome to-day by using cable-tool core-barrels which lead to the successful recovery of good cores with practically all types of rock; such core-samples are dealt with in the same way as other cores obtained from rotary drilling systems.

Core Samples.—The notable advance made in technique of subsurface stratigraphical identification and correlation, whether dependent on heavy minerals, micro-organisms or study of thin sections, is due largely to the greatly increased facilities for obtaining substantial core samples of the rocks traversed, now offered by modern drilling equipment. In the case of hard, consolidated rocks, the cores as recovered should in all cases be comparable with the same materials had they been hammered out *in situ*. Apart from any petrographic or palæontological evidence of the rock succession which such cores may reveal, their use when properly controlled and interpreted is of first-class importance in elucidating subsurface structure.

The utility of core samples will depend to a large extent on their diameter, decided by the nature of rock and depth of the boring concerned. In many formations small cores are inadvisable if the larger organisms are sought for evidence, but for obtaining maximum stratigraphical and structural information, anything over 3 in. is in general satisfactory. With 6 in., 12 in., 18 in., or even larger diameter cores, the geologist should have in all normal circumstances the best material he can expect from otherwise inaccessible rock.

Where soft and incoherent rocks are involved, coring is frequently a matter of difficulty and the recovered samples are apt to be discontinuous, broken and possibly contaminated. Formerly there was considerable difficulty in obtaining pure samples of such rocks with practically all drilling systems, especially with the rotary where no coring gear was available. Quite an appreciable amount of difficulty encountered in microscopical investigations of such rotary material was traceable to interferent matter from mud-flush, particularly if heavy mineral mud, e.g. barite, hematite, was employed for any reason. Modern drilling facilities have considerably decreased such difficulties, though the problem of contamination of soft sand

and clay samples, whether in oil or water borings, has frequently still to be faced.

At this point it must be emphasised that, apart from possibilities of contamination with softer rocks, continuous coring of a given bore-hole, whatever rocks are concerned, while theoretically desirable from a geological standpoint, is not always practicable either on the score of the nature of the rocks penetrated (*e.g.* cavernous limestone, loose detritus) or of expense.

In oilfield practice, unless continuous coring is specified, core-samples are generally taken at regular intervals where little or nothing is known of the subsurface rocks; such intervals may be every 30 ft., 20 ft., 10 ft., or less in exceptional circumstances; where more is known of the rocks being drilled, the intervals may be much greater until critical horizons are reached, such as oil-sands, cap-rocks etc., when close coring becomes a matter of necessity.

That the use of the core-barrel does not eliminate the contamination factor is due to the fact that drilling mud is liable to "pack in" with the rock, especially if the latter is soft or when drilling pressure is high. Many of the core-samples examined by the author have obviously suffered contamination in this way, in some cases the heavy mineral assemblage varying from different parts of the same core! A. C. Rubel¹ has discussed some pertinent aspects of this question of contamination and has shown how in some cases the drilling mud may not only coat the outside of the true rock-core (which frequently happens), but may be forced to penetrate a loose sand, for example, giving rise on compaction to a core of alternate sand and mud, instead of a core of definite sand, with resulting inaccuracy in "logging" the well, to say nothing of the ultimate petrographic examination. Another case in the author's experience is where the drilling mud itself gets cored, *e.g.* when drilling through fine mobile sand which, masked by the flush, results in the erroneous record of "mud," "shale," "gumbo" etc.

To guard against misleading appearances and possibilities

¹ "Determination of Core-Samples in Core Drilling," *9th Ann. Rep. Calif. State Mining Bur.*, 9, 1924, No. 11, p. 5.

of this nature, the following precautions should always be taken before submitting cores to treatment for petrographic or other analysis:—(a) with soft rocks always scrape off the outer margin of the core; with a 3 in. core, for example, this implies discarding at least $\frac{1}{4}$ in. to $\frac{1}{2}$ in. of outside material; (b) take the interior of the sample for investigation wherever possible; (c) at frequent vertical intervals, as represented by the cores, split a sample longitudinally to ascertain whether any extraneous material (drilling mud) has penetrated the rock; if this has happened it will usually be indicated by the inter-digitation of the mud and the rock, the mud-laminæ being continuous with the mud forming the outside coating to the core; (d) if a mud-flush is used in which the mud is obtained from the same supply throughout the drilling of the well, take a sample of the material (silt or clay) employed from time to time and examine carefully as a check on possible impurities. Often the mud employed is furnished by the finer shale- or clay-cuttings obtained during the early drilling of the well so that, unless care is taken, critical constituents of a higher horizon may quite easily find their way into deeper cores and thus be misinterpreted in subsequent examination. It is apparent, however, that the possibility of contamination is greater the softer the rock; on the other hand, with hard rocks the percussion drilling system is resorted to and where the hole is being drilled dry, or nearly so, or where a cable-tool or other form of core-barrel is employed, the contamination factor may be expected to prove far less serious.

Fauk System Samples.—What is known as Fauk's patent "Express" drill produces in normal circumstances good cores from all kinds of rock, but chiefly from those which ordinarily are drilled with the standard cable-tools. The system is in principle a water-flush one, but it is also adapted to dry drilling and in either case the samples obtained are quite reliable and tend to be uncontaminated.

Diamond Drill Cores.—Where a diamond drill is used, the core-samples are probably less contaminated than those obtained by any other means; in fact, except with very loose sediment, this system of drilling provides the geologist with some of the very best material for ultimate microscopical

examination. "The value of the solid core secured by the diamond drill cannot be over-estimated. These cores show in exact sequence the various rock-layers pierced and record accurately the depth, thickness and character of each one, together with its dip and strike. As compared with ordinary drilling methods which merely furnish cuttings brought up by the return water, the diamond drill core represents definite, complete knowledge, the other, guess work."¹ Quite apart from the investigation of micro-organic or heavy mineral constituents extracted from such cores by crushing, this form of well-sample lends itself more readily than any other to analysis by means of thin sections.

Core-sample "splitters" and extractors are supplied as part of the standard coring equipment for all drilling systems.

Oilfield Sample-Container.—For hard or repeated use, the ordinary canvas bags or unprotected tins are of little use as sample-containers and in oilfield practice it is customary to employ a strong pattern wooden container for transporting samples from drilling wells to the laboratory, also to prevent as far as possible any mixing of materials either on the derrick-floor or subsequently during conveyance. This type of container is so consistently successful that it may with advantage be used in other circumstances where systematic sampling is contemplated.

The pattern recommended by the author consists of a flat, shallow wooden box, with lid, constructed externally of $\frac{3}{4}$ in. or $\frac{1}{2}$ in. white wood (teak for the tropics) and of such dimensions that it may be subdivided inside by $\frac{3}{4}$ in. partitions into twelve cells, each cell being capable of accommodating either a rectangular tin 3 in. x 3 in. x 4 in. or a round cigarette tin (50 size); both forms of tin should have lids. The container is fitted with substantial hinges and fasteners and a handle, usually of leather, is attached to the front in a similar position to the handle of an *attaché* case.

For core-samples, special open rectangular wooden trays, longitudinally partitioned, are generally employed. These depend for dimensions on the diameter of the cores taken. In the case of 3 in. cores, for example, the convenient tray is one

¹ "Diamond Drilling for Oil." Sullivan Machinery Company, Chicago, 1923, p. 9.

which accommodates in six divisions 36 ft. of core, *i.e.* 6 ft. per division. More core per tray, especially if the diameter is larger, results in very heavy, unwieldy containers, though where labour is not difficult this may be no drawback. Such core-trays are used both on the wells and for permanent storage.

Labelling of Samples.—A word of warning is here necessary in cases where no core-trays are employed. Ordinary drilling practice, especially with borings for water in this country and elsewhere, is to mark at convenient, though often irregular, intervals the recovered cores, usually with an indecipherable dab of black paint, either numerals or hieroglyphics being employed, to represent depth in feet. The cores are then laid out in more or less parallel lengths alongside the rig, exposed not only to the vicissitudes of weather, but to the deprivations of all and sundry who suddenly want some lumps of rock for weighting down tarpaulins, corrugated iron, or for other purpose on site, or of those whose nearby gardens or allotments may secure some adornment by perquisites of an unusual character.

Unless very strict instructions are given, the last thing the driller usually worries about is the cores; the geologist, if he is not continuously on the job, may soon find that half the value of careful coring during the progress of the work is destroyed by inability to mark correctly, place properly and guard cores once taken. The author writes from bitter experience of this kind of thing and also with a wholesome distrust of the memory of the drilling crew, who may afterwards attempt to make good the damage by placing the cores correctly (?) in the supposed order of succession.

In all cases where close or continuous coring is decided upon, it is the geologist's duty to advise his principals very definitely regarding the lay-out of these core samples; in cases where he has a reasonable knowledge of the rocks to be penetrated, it is often possible to instruct the drillers at exactly what intervals of depth to mark cores; alternatively, to mark every lithologic change, whichever is the more appropriate. Furthermore, the marks (numerals) should be made distinctly and with a waterproof black paint (preferably bituminous) specially supplied for the purpose. It should also be made incumbent on

the driller to record in his log book the corresponding series of depths at which the samples are marked, quite apart from his usual fanciful description of the rocks penetrated.

When dealing with a large number of samples other than cores, the possibility of confusion has equally to be guarded against. Much trouble of this kind can be avoided by careful and systematic labelling. All samples, whether consolidated rock specimens or loose material in sample-boxes, bags or other containers, should be clearly numbered as soon as they are collected, serial numbers in conjunction with an index-letter denoting a given area or locality being preferable; thus differentiation from previously collected material is automatically made. In oilfield practice the field or lease (often signified by a letter of the alphabet or suitable field-sign), the well number and depth, are desirable, *e.g.* "B.B. 27—1875"; *i.e.* "B.B." lease or field, well No. 27, depth 1,875 ft.; the next sample might bear the label "B.B. 27—1890" and so on. When a given series of samples from the same well is in process of investigation in the laboratory, the depth numbers obviously suffice for reference.

Permanent Storage.—Methods of storing samples vary largely according to taste, custom, facilities, climatic conditions and the nature of the materials. With loose sediments or "cuttings," glass bottles with wide necks and corks or flat-topped stoppers to fit are employed where large quantities of material are required. For small quantities, storage is effected either by cardboard containers (cylindrical with screw tops), strong canvas-lined envelopes or glass specimen-tubes; the author favours the latter receptacles, especially those with screw metal tops, size 3 x $\frac{3}{4}$ in., 4 x 1 in., 5 x 1 in. or 6 x 1 in.; where cheapness is a desideratum, 4 x 1 in. tubes with flat corks are quite good. Cardboard or canvas containers are apt to be destroyed by insects or mice, especially in hot countries, or they may suffer quickly from damp. Glass has the disadvantage of being liable to breakage, especially in transport; tins resist attacks of insects and to some extent damp, but they quickly rust if not kept in dry surroundings.

Always put a label inside the sample-container as well as on the outside.

With core-trays, it is usual to paint or otherwise mark on both ends of the container the field-sign, well number and limiting depths represented by the cores inside; the boxes are then stored side by side on suitable shelves in such a way that the "end-labels" can be rapidly read and any given series of cores referred to easily. The cores from one well are always kept together. In the case of larger diameter cores, this method of storage may prove impracticable; it then becomes a question as to whether the whole core suite shall be kept or, once the necessary evidence is obtained, only representative pieces from critical horizons; in the latter event, the material is usually dumped in an appropriate place or, as may well occur on isolated sites, if the rock is suitable, utilised for road construction. Whatever happens, the responsibility should rest with the geologist.

Key-Samples.—The advantage of setting aside small portions of important samples for future reference and comparison with material subsequently obtained is sufficiently obvious to require no further emphasis. Such "key-samples" may be representative of particular stratigraphical subdivisions, zones, horizons, oil-sands, water-sands, prolific foraminiferal clays etc., and are independent of any microscope slides of mineral residues or organisms ultimately prepared.

Of a similar significance are the specific outcrop specimens collected for purposes of comparison (on analysis) with equivalent rocks likely to be met with in well-samples; see p. 60.

Sample-Indexing.—The storage space necessary for the accommodation of many rock-samples is liable to grow considerably in excess of laboratory facilities for this purpose; hence some system of indexing or filing information concerning samples soon becomes essential and, in point of fact, is much favoured in laboratories concerned with work of this kind. The samples can be stored outside in a suitable storehouse, shed or similar place, while the card-index is a requisite part of the laboratory equipment. Generally a card is devoted to each sample (in the case of oil-well samples) and contains information regarding field or lease, position, name and/or number of well, depth, geological horizons proved and other relevant data. In some cases a separate card-index is made for recording petrographical and/or palæontological data obtained from certain

samples, for the purpose of rapid reference when carrying out microscopical examination of new material and to save time in searching a number of different and possibly irrelevant slides; or such information may be logged on the one card.

Index-cards and files vary according to requirements; a useful size is 8 x 5 in., which provides enough room (both sides)

FIELD	X. Y. Z. Co.		SAMPLE No	DEPTH ¹ 2190 ft.-2195 ft.
WELL No.	HORIZON		CASE No.	
FORMATION	By WHOM TAKEN		DRAWER No.	
SAMPLE ²	DATE			
DRILLER'S LOG ³	COLOUR (W or D) ⁴			
MEGASCOPIC DATA	REMARKS ⁵			
VISIBLE ORGANISMS				
TEXTURE	GRADE	SHAPE	ACCESSORY MINERALS	
MICRO. ANAL. ⁶	THIN SECTION No		PER CENT TOTAL SAMPLE	
			AVERAGE GRADE	
			AVERAGE SHAPE	
			SPECIAL FEATURES ⁷	
(SEE OVER FOR DETAILS) ⁸				

Fig. 1. Specimen Well-Sample Card as designed and used by the author. Actual size 8 x 5 in.

NOTES — 1—Depth-range is inserted boldly in top right-hand corner to facilitate reference when in file. 2—State here whether core, cuttings etc. 3—Description as entered in driller's log. 4—W = wet, D = dry. 5—Insert here any special observations of f. oil, asphalt, water-sand etc. 6—Microscopical analysis. 7—Note here any peculiar index-minerals or characteristics of the suite. 8—Reverse side of card used for list of minerals or special data.

for all possible information. A suitable standard type for well-samples is reproduced in *Fig. 1*.

To obtain the fullest use from a card-index system of this character, it should be used in conjunction with graphic well-logs of each well drilled. Incidentally, special samples, water analyses, oil and gas horizons etc., can be logged on different coloured cards placed in proper sequence with the sample-cards.

Sampling from Bulk for Laboratory Analysis—Quartering.—It is frequently necessary to reduce bulk rock, either lump, crushed or naturally incoherent, such as gravel, sand etc., to workable size for laboratory investigation, whether this involves chemical, microscopical or physical tests. In such an event the ultimate sample must be truly representative of the bulk in order that results may reflect inherent properties of the mass as faithfully as possible. To achieve such a sample the utmost care and systematic procedure are important. Sampling is an art in itself. It requires both knowledge of such procedure and experience in applying it.

It should be remembered that everything depends on the efficacy of initial sampling. If errors creep into this, analytical results may be entirely vitiated. Further, in certain circumstances it may not be practicable to re-sample the bulk for repeat tests, if results are suspect; whereas if the sample is correctly obtained in the first place, repeat tests can be made with the assurance that whatever error may have occurred, it is not due to sampling.

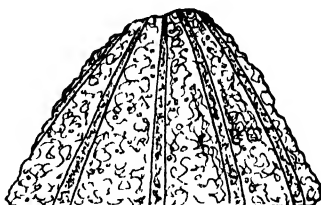
Actually scientific sampling of large bulk material is quite a complicated business demanding considerable skill. Some idea of what is involved in extreme cases, both in theory and practice, is obtainable from the specifications for sampling coal, to which the reader is accordingly referred.¹ For all practical purposes with ordinary rocks, procedure can be simplified to reduction of bulk by quartering and is determined by the nature of the rock to be sampled, size of the available bulk from which the sample is to be prepared and variation (if any) in size of components. Details of the procedure to be adopted in sampling such materials as sands, aggregates and fillers, to-

¹ British Standard Specifications 403—1930 and 420—1931.

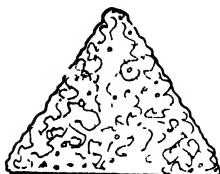
gether with information regarding the size of sample to be taken, will be found in a recently issued British Standard Specification.¹



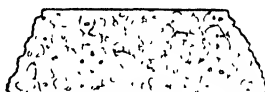
Original Heap.



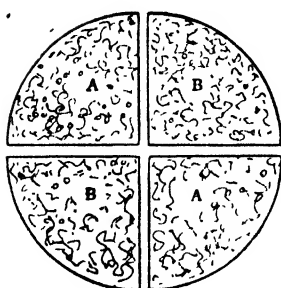
Furrowed Heap.



Cone.



Flattened Cone.



Carving.

Mixed Quarters.
A, A.

FIG. 2. Sampling from Bulk—Quartering.

In the case of material of mixed grade such as "all-in ballast," the following procedure will be found effective.

¹ No. 412—1938.

Assume a heap of 5 cubic yards (approximately $5\frac{1}{2}$ tons). Select a series of places at approximately regular intervals round the heap, say every 3 ft. With a shovel remove the outer material from the top downwards to form distinct furrows; such material should be rejected. Then attack each furrow in succession from the bottom, working upwards to get a representative shovelful. Three shovelfuls should be taken from each furrow and the shovelfuls mixed together on a clean, flat surface (*Fig. 2*).

The next stage is "coning." Heap the material obtained into a cone by shovelling small quantities at a time one on top of the other, taking care to keep the cone as true to shape as possible. If desired this coning can be repeated by systematically breaking down the first cone (working from the base) and forming another alongside. Once the final cone is made, flatten by pressing the shovel on to the apex, thus reducing the mass to a flattened pile of circular cross-section and uniform thickness. Next carve the mass through with the shovel with two right-angle cuts so as to divide it into four quarters, separating the material slightly with a lateral movement as the cuts are made. Remove two opposite quarters and reject them. Re-mix the remaining quarters completely in the form of a cone, flatten, re-quarter as before and reject opposite quarters. Repeat the process until a sample of desired size is achieved. In the case of "all-in ballast" taken as example, it is assumed that sizes range from $2\frac{1}{2}$ in. pebbles down to coarse sand (0.08 in.), in which case, from 5 cubic yards an ultimate sample of approximately 2 cwt. would be adequate to submit to the laboratory where, according to the particular tests to be made, it would be re-sampled by crushing, quartering, grading etc.

It should be realised that in taking samples of material containing a large assortment of sizes, such as above, it is always difficult to maintain and preserve accurately the initial ratio between coarse and fine detritus in the final sample. Great care is necessary to avoid overloading shovelfuls with coarse material which naturally tends to fall from the top of the heap when dislodged. Aggregates of this description should, if possible, never be sampled if exposed to wet weather or if they have lain long in the open, owing to the tendency for

finer sand either to be washed down or else to gravitate to the bottom, there to concentrate.

Where grading is more uniform, even of coarse material such as crushed granite or flint or naturally graded, uniform gravel or grit, the above difficulties are less likely to arise and procedure will be as described.

Where crushed rock, powder, sand or fine, uniform filler is concerned, much the same process is involved. If the initial bulk is small it should be well turned over before commencing to sample. Shovelfuls should be taken at regular intervals, coning and quartering to suit. If the bulk is large, a similar procedure of attacking it at regular intervals around the periphery as described above will be necessary; alternatively, with rock powder, fillers etc., the material may be sampled with a scoop (about 1-lb. capacity) from various points on the heap, each scoopful being emptied into a cask or suitable container, after which coning and quartering proceed in the usual way. With such material, it is also possible to use an auger, which can be made out of suitable brass tube in which is cut a longitudinal slit; the bottom end of the tube is tapered and the top end is fitted with a strong handle similar to that on a motor car tyre pump. The auger is inserted at regularly spaced intervals and made to penetrate as deep as it will go. Each withdrawal carries representative material from depth of the mass and this is emptied into a cask until the requisite quantity of the filler is obtained for quartering. The auger method is particularly useful for fillers stored in sacks or barrels.

Finely divided material, if of uniform grade, should always be sampled in as dry a state as possible.

CHAPTER III.

LABORATORY TECHNIQUE.

Dry Samples — Megascopic Examination — Thin Section Preparation—Schedule of Equipment—Points in Mounting Friable and Impregnated Rocks — Mounts other than with Canada Balsam — Impregnating Friable and Porous Rocks—The Use of Synthetic Resin—Conventional Thickness of Rock-Sections—Treatment of Incoherent Rocks for Heavy Minerals, Micro-Organisms etc.—Schedule of Equipment—Single Heavy Mineral Separations—Heavy Mineral Sampling—Mounting of Sand Grains for Microscopical Examination—Systematic Procedure for Simultaneous Investigation of Samples for Micro-Organisms and Heavy Minerals—Special Methods of Concentration—Centrifuge Methods—Heavy Liquids and Substances other than Bromoform for Mineral Separation—Detrital Mineral Concentration by Hand—Elimination of Proliferous Minerals from Heavy Residues—Treatment of Argillaceous, Calcareous, Carbonaceous, Bituminous Impregnated and Crushed Rocks

Dry Samples.—Sedimentary (incoherent) rock-samples should be thoroughly dried before examination. Oil-well samples are generally wet and in this state are apt to prove misleading in diagnosis, particularly if any oil is present. Where a number of samples is being constantly handled, the most convenient and satisfactory means of drying them is on a long rectangular iron plate, about $\frac{1}{4}$ in. thick, suitably supported on tripod-stands and heated by bunsen gas-burners or, in the absence of gas supply, by ordinary oil-stoves; in the latter case the iron plate may be supported on trestles with pieces of asbestos inserted between the wood and the iron. The samples are emptied from their containers, spread out on square-cut pieces of paper or filter papers of suitable size, placed on the plate and thus left to dry. Care should be taken not to over-heat the plate and char the paper.

Megascopic (Macroscopic) Examination.—Prior to special treatment for detailed analysis, the maximum information should be obtained from samples by eye-inspection, aided with a hand-lens and also with a binocular microscope, if available

and where relevant (p. 155), such information being recorded at the outset on the appropriate index-card (p. 26) or in a sample record-book. The following are the chief points of observation :—

- a. Identification.
- b. Colour.
- c. Texture.
- d. Composition (inorganic constituents).
- e. Fossils or organic structures.
- f. Bedding, lamination, cleavage etc.
- g. Special structures or characteristics.

a. Specific identity may not always be possible without recourse to thin sections or special tests (p. 62). The chief difficulties arise with compact, fine-grained rocks, *e.g.* limestone, marl, salt, anhydrite, gypsum, while different coloured shale or mudstone fragments may simulate other types. Knowledge of what to expect from any particular horizon may help, but doubtful cases should always be subjected to exhaustive investigation before "labels" are applied with confidence.

b. Colour varies markedly in sediments according to whether the samples are wet or dry. Frequently the former state aids diagnosis, but inherent colour must be determined in the dry rock. There are standard colour-systems in use by some petrologists, *e.g.* Munsell, Ridgway,¹ and N.R.C.C.S.² schemes, which are useful for comparative purposes. Note should be taken as to whether the colour is due to particular ingredients, whether it is superficial stain or tarnish, a weathering product or inherent to the rock as a whole.

c. The coarse, medium, or fine texture of a rock should express relationship to its actual mechanical analysis but, short of quantitative data, the terms are purely comparative. Experience of varied sedimentary rock-types and an "eye" for grade-size of components, however, enables the observer to use these terms more or less accurately. Texture should apply as an average to the specimen as a whole, but may, of course, be restricted to cementing material independently of the large con-

¹ R. Ridgway, "Colour Standards and Colour Nomenclature," 1912.

² National Research Council, Committee on Sedimentation (U.S.A.). Colour-Chart obtainable from headquarters, Washington (D.C.).

stituents, *e.g.* conglomerate with $\frac{1}{2}$ in. pebbles set in a *fine* compact matrix. The art of "textural analysis," as it is called, is of recent introduction; as a quantitative estimation, its consideration is deferred to subsequent paragraphs (p. 212). Qualitatively, clay, marl, siltstone (components <0.1 mm.) imply fineness of texture, individual particles being practically invisible to the unaided eye in the case of siltstone, entirely so in the argillaceous types. Normal sandstones, grits and the like, frequently approximate the size-limits 0.25 mm. — 0.5 mm., and are thus correctly labelled "of medium texture." Above the larger dimension, the particles assume characters which tend to guide the observer to the correct definition "coarse," especially 1 mm. and 2 mm. particles, while the presence of pebbles automatically leads to this description unless the matrix alone is considered (*supra*). Limestones devoid of visible organic remains are usually of the compact, fine textured type; so-called "shelly" limestones approximate the coarser rocks; oolitic types vary from medium to coarse texture, pisolitic varieties invariably coming under the latter category. *Shape does not affect the question of texture.* Texture has some bearing on "tightness" or "openness" of rocks acting as oil-containers, though it must be remembered that it is not alone an indication of porosity or permeability.

d. The composition (inorganic constituents) is essentially a record of the lithology of the sediment and implies recognition of those features characteristic of particular rock-types, *e.g.* sandstone, grit, arkose, quartzite, shale, marl, limestone etc. Naturally it also implies the mineralogy of the sediment in so far as this is determinable without microscopic aid. In the coarser rocks the shape of the prominent constituents, angular, subangular or rounded, comes into consideration, especially where pebbles are concerned (p. 117), but in the majority of cases "shape" of particles is more accurately recorded under the microscope (p. 158). Other points to note under this heading are surface characters dependent on weathering (if any), the uniformity or heterogeneity of the components and any unusual lithologic features.

e. Fossils or organic structures, whether determinable or not, should be recorded as such when occurring in the rock.

Obviously, if determinable, the rock becomes distinctive at once; if not, even the presence of organic remains, either vegetable or animal, is of some diagnostic value. There is seldom difficulty in recognising constituents as organic remains, even if they are not sufficiently well preserved to afford clues to their precise nature and origin; a hand-lens is always effective in this connexion. Some distinction should be made between dominantly fossiliferous rocks, those which are only partially fossiliferous and those of which the organic remains are few and far between. The orientation of the organisms should also be noted. The nature of the petrification is important; it may be calcareous, siliceous, pyritous, phosphatic, limonitic, more rarely other minerals. The calcareous forms include calcite and aragonite preservation; in the former category fall most of the vitreous forms of *foraminifera*, many sponges, corals, echinoderms, polyzoans, brachiopods etc.; lamellibranchs consist mainly of aragonite (except the common *Ostrea* and *Pecten*), as also do gasteropods (excluding some species of *Fusinus*), porcellaneous forms of *foraminifera* and cephalopods (ammonites frequently show much secondary calcite and pyrite); in crustaceans the shell usually consists of chitinous material, calcite and phosphate of lime.¹ Where only casts or impressions of the organisms are seen, the nature of these should be carefully ascertained and, if desired, wax or plaster moulds taken. Note the significance of the presence of glauconite in association with organic remains (p. 506).

f. Distinction should at once be drawn between specimens exhibiting bedding or lamination, cleavage, or any linear or curvilinear structures and those devoid of same. Note whether the bedding, if developed, is uniform or variable, thin or thick, regular or cross (current-bedding); whether shaly-lamination is apparent or not; whether the bedding-surface is smooth, flat, crumpled or rippled and, if the latter, the nature of the marking (symmetrical or asymmetrical); cleavage, though it may be clearly apparent to megascopic observation, is better studied in thin section, especially in its relationship to reconstituted minerals etc.

g. Special structures or characteristics are those which

¹ H. Woods, "Palæontology." (University Press, Cambridge), 1909, p. 4.

tend to give individuality to any particular rock-type, such as surface-markings, mud-cracks, rain-prints, worm-tubes, -tracks, -impressions, mineral "spots," peculiar modes of weathering, minute warping and shear-structures, angular jointing (with bedding or cleavage), secondary mineral developments as veins, blebs, cavities, bituminous impregnations, distinctive constituents etc.: in short, any feature which, by its conspicuous and possibly widespread development, tends to individualise the rock and thus render its identification and history easy of interpretation.

Thin Section Preparation.¹—Methods of thin section preparation are now so generally known as to require only brief treatment here. It may be observed, however, that in general sedimentary rocks demand a greater degree of skill in the manufacture of really thin slices, owing to their inherently softer and more friable character, than igneous rocks; in fact, many sedimentary rocks demand special treatment and technique before sections can be made from them at all; such departures from normal routine are discussed in the sequel (p. 40).

It must also be born in mind that field-laboratories are not usually equipped with elaborate rock-cutting machines and that hammered fragments from outcrop specimens or, as is more common, well-sample chips or core-flakes, constitute the only available raw materials. It requires considerable experience and skill, for instance, to take a bailer cutting of, say, $\frac{3}{8}$ in. diameter (perhaps the largest piece available of a critical rock-horizon penetrated) and produce therefrom a satisfactory slice which will respond to the most refined optical examination; however, it can be, and often is done with remarkable consistency by lapidaries who really know their work.

Schedule of Equipment.—While it is freely admitted that individual taste and experience play a large part in the selection of appropriate apparatus for this work, the author has found from long experience that the following equipment is most economical and satisfactory for all field-laboratory purposes, or for those operations where neither personnel, time nor money is available for large-scale procedure and output:—

¹ For fuller data see H. B. Milner and G. M. Part, "Methods in Practical Petrology." (Heffer, Cambridge), 1916.

- Steel Plate (machined) for coarse grinding, circular, 12 x 1 in. or 12 x $\frac{1}{2}$ in.; alternatively square, 12 x 12 x $\frac{1}{8}$ in.
- Glass Plates with ground edges, square, 12 x 12 x $\frac{3}{8}$ in. for medium and fine grindings.
- Wooden Trays (3), preferably teak (essential wood for tropics) to accommodate above plates, 13 $\frac{1}{2}$ x 13 $\frac{1}{2}$ x 1 in. deep (inside dimensions).
- *Copper Plate (hard drawn) about 15 x 4 $\frac{1}{2}$ x $\frac{3}{16}$ in. for heating balsam on glass slips, to accommodate 12 at a time.
- *Tripod Stands (2) to hold copper plate, 8 or 10 in. high, depending on burner used.
- *Microscope Slips, clear glass, ground edges, 3 x 1 in., 0.75 mm.-1 mm. thick (supplied by the gross).
- *Cover Glasses, No. 1 quality, rectangular, $\frac{7}{8}$ x $\frac{7}{8}$ in. (Approximately 1 oz. per gross of slides.)
- *Forceps, polished steel or nickel plated, with ribs and fine points, 10 cm. long.
- *Soft Tooth-Brush for removing surplus balsam in methylated spirits.
- *Photographic Developing Dish ($\frac{1}{2}$ -plate size) or large Evaporating Basin for cleaning slides.
- *Canada Balsam (*filtered*, not solution in Xylol) in 1 lb. bottles (coloured glass).
- Carborundum: grit 90 for coarse grinding, grit 220 for medium grinding, minute powder 60 mm. for fine grinding.
- Emery Powder FFFF for fine grinding and special work.
- Putty or Rouge Powder for polishing rock-surfaces.
- Shellac Flakes for "cooking" friable or soft rocks (mix 2 parts of balsam and 1 part shellac).
- Bakelite Cement for friable rocks.
- *Methylated Spirits, Benzol or Xylol for removing surplus balsam (the first recommended for preference).
- Glycerine for special "dry" grinding.
- *N.B.—These materials are also used in the mounting of incoherent sediments, heavy mineral residues and the like. When indenting for the above equipment, quantities should be ordered which are commensurate with the work in view and with the facilities available for replenishment of supplies as materials become exhausted.

If some form of rock-cutting machine is employed, add to the above list the following:—

Spare cutting discs.

Extra supply of coarse carborundum.

Diamond Dust ("Diamond Splint").

Flint Pebbles for bedding diamond dust in cutting-disc edge.

Thin lubricating oil or paraffin.

The following procedure applies to normal hard rocks, whether igneous, sedimentary or metamorphic. The fragment is first ground down with coarse carborundum mixed with water on the steel plate until as large an area as possible, of uniform surface, is obtained. It is then washed free of carborundum and transferred to the medium (glass) plate, where a similar grinding with medium carborundum reduces the sur-

face still further, removing all scratches etc., due to the coarse grinding and preparing the flake for the next grinding on the fine plate, using "minute powder" or emery as detailed above. The utmost care should be taken to see that no coarse carborundum finds its way on to the medium plate and that no medium powder has access to the fine plate, otherwise the plates will soon be ruined, if not the slices under preparation; this possibility is easily avoided by careful washing under running water between each grinding and by keeping each of the trays some distance apart. After a satisfactory surface has resulted from the fine grinding (it should show no scratches or blemishes of any kind), the chip is well washed, then dried on a hot plate.

It is often found that with many sedimentary rocks the coarse abrasive is too drastic and a cautious use of the medium grit is all that is necessary to secure both rapid and successful results. In soft rocks it may only be practicable to grind steadily with minute powder or emery, whichever is preferred, if a reasonable sized fragment is to be salvaged from disintegration. Much of this trouble can, however, be obviated by preliminary cooking of brittle or perforated rocks in the shellac-balsam mixture (above) for half an hour previous to grinding; use a tin-lid on the hot plate for this purpose. In special cases it may be necessary to resort to dry grinding (p. 40) or to some form of resin impregnation (p. 42).

Once the rock-chip is dried after the first grindings, the next operation is that of mounting it on the glass slip and on this process the ultimate success of the work depends. First mark at the bottom end of the slip the reference number of the rock; this is done with a diamond and ensures that no mixing up of specimens occurs (where a number is being cut together). The rock-chip is mounted on the side of the slip *not* marked with the diamond. This obviates any danger of the reference number being removed in the subsequent grinding. Then proceed as follows:—"some balsam is spread on the glass slide and heated on the copper plate. It is sufficiently cooked when a thread drawn out between the points of a pair of forceps becomes brittle when cold. *Insufficiently cooked balsam will absorb carborundum during the second grinding. Overcooked balsam is too brittle and will break*

away, thus exposing the edges of the rock-chip which it is there to protect. When the balsam is just right for mounting, the rock-chip, which has also been heating meanwhile, is placed, polished surface downwards, on the slip and firmly pressed down, care being taken to exclude air-bubbles. If any of these remain, the slip must be reheated and the chip worked about until the bubbles are pressed out. When cold, the second grinding may be proceeded with."¹

When thoroughly cold and firm, the chip is ground down once again on the coarse plate, if it initially stood this abrasive, until it is about 1 mm. thick, the glass slip being used as a convenient holder. The surface attained, it is washed and transferred to the medium plate where further grinding with the 220 grit reduces the chip to a state of translucency. It is washed again and finished on the fine plate. If during the final grindings balsam tends to come away from the rock, either transfer the latter to a new slip on which a fresh supply of balsam has been cooked in readiness, or pour suitably cooked balsam on to the specimen so as to surround the exposed edges completely and allow to harden.

In the final stages of grinding on the fine plate, great care must be taken to avoid unequal pressure on different parts of the slice; if there is a tendency to thickness in any particular area of the slice, it may be checked by grinding that part on the edge of the plate until uniformity of surface is obtained. Check carefully and often the progress of operations with the microscope, using crossed nicols to ascertain thickness (p. 167).

When the slice is of requisite thinness, dry cautiously on the hot plate until all moisture is driven off. In the case of normal hard rocks, fresh balsam may be placed on the dried chip, slowly cooked to the right degree and then covered with the cover-glass on which a thin coating of balsam has also been allowed to cook. With soft rocks it is advisable to cook the fresh balsam on a separate slip and then to pour it on to the dried slice, following this operation at once by placing the cover-glass in position as in the first case. Air-bubbles are expelled by gentle pressure with the forceps on the cover-glass while the balsam is in a fluid state.

¹ H. B. Milner and G. M. Part, *op. cit.*, p. 9.

An alternative, neater and more skilful procedure is to transfer the finished slice to a new glass slip on which adequately cooked balsam is ready to receive it. With hard compact rocks, this may not present great difficulty, but with softer, coarse textured examples it is a different matter altogether. In fact it may be said that the skill of a lapidary is directly proportional to his or her ability to achieve successful transfers with almost all rock types.

The best way to proceed in transferring is as follows:—on to the finished dry and cold slice on the original glass slip, pour enough properly cooked balsam to cover same and place the slip alongside a new glass slip (also with properly cooked balsam) so that their long edges coincide and the balsam from each amalgamates. When this happens, ease the rock slice from the old on to the new slip in the balsam medium with the blunt point of forceps, then take the new mount off the hot plate and press the slice gently down to expel air bubbles. It is important in this procedure to see that there is no difference in thickness between the two glass slips in use, otherwise if there is a “step-up” or “-down,” the slice will inevitably break during transfer.

Sometimes it is possible to vary this procedure by holding the original slip with the rock slice over the hot plate at an inclined angle to the new slip and as the slice gets warm gently sliding it down into the cooked balsam on the new slip ready to receive it.

The final operation is to clean the slide. With the cover-glass in position and the air-bubbles expelled, the slide is allowed to cool and then all surplus balsam adhering to the edges of the slip is cleaned off with a soft tooth-brush in methylated spirits. The cleaning process may be accelerated in skilful hands by flaking the solid balsam with a sharp knife, then cleaning with xylol, but care must be taken to see that the cover-glass is not damaged in the process; also that the xylol does not dissolve the balsam from beneath the cover-glass. When clean, polish the slide with wash-leather and label with $\frac{7}{8}$ in. square labels at each end. In this connexion it should be remembered that gummed labels may perish or become detached in the tropics; in such cases grind each end of the slide

on the coarse plate until opaque, if this is not already achieved, and print the description of the slide with Indian ink on the surface thus produced. Alternatively, an identity mark or number can be scratched on the slide with a diamond, or etched with hydrofluoric acid on a wax-covered area, the wax being suitably incised with a fine wire point; this last, however, is a tedious and not very satisfactory procedure.

Points in the Preparation and Mounting of Friable and Impregnated Rocks for Thin Section Examination.—Those who have had experience of producing thin sections of friable rocks or bituminous impregnated sediments are aware of some of the difficulties occasioned by these types; the tendency of the former to crumble or disintegrate, if not in the early stages of grinding, often just before the section is achieved, and the trouble caused by fluxing of the bitumen when mounting with warm Canada balsam in the case of the latter, are familiar troubles to be overcome. In these connexions, E. J. Tallin of the Geological Department, Imperial College of Science and Technology (to whose skilful preparations of thin sections of such rocks the author has on many occasions been indebted in the past) has contributed the following brief account of his own technique :—

“ Before proceeding with the usual grinding of such rocks as clays, shales, some limestones, certain loosely cemented sandstones, lignitic material, schist and any weathered or much altered rock, the slice to be sectioned should be thoroughly warmed to get rid of any moisture present. It should then be immersed in a bath of Canada balsam and cooked until this medium is tough but not brittle, just hard enough, in fact, to be impressionable with the finger-nail. When quite cool, the grinding of the slice may be proceeded with in the usual way.

“ The above method is not applicable to bituminous rocks since in these cases slight warming causes the bitumen to migrate, either leaking out altogether, saturating parts of the rock not previously saturated, or fluxing with the Canada balsam. The effect of such movement is likely to give an erroneous impression of the impregnation when the section is examined under the microscope. Also, many of these rocks on warming become warped, even corrugated, thus preventing the achievement of a uniformly thin section. Again, certain constituents of oil-bearing rocks are soluble in water, hence these are lost if the ordinary methods of preparation are adopted.

“ Dry cutting such rocks is therefore advisable, the cutting disc being lubricated with a little glycerine. The slice thus obtained is carefully ground on a metal plate with 3F carborundum, then with washed flour emery, and lastly on a Water of Ayr Stone, using glycerine as before. Canada balsam used for mounting the slice is previously cooked before it is poured on to the glass slip, and the slice must be quite dry

before it is mounted. The second grinding is carried out on a carborundum cloth (grit 90) fastened down to a flat surface, and is proceeded with until the slice is flush with the surface of the balsam. The back of the glass slip should be periodically examined for 'flaking,' *i.e.* fracture of contact between the slice and the slip. Final grinding is carried out on fine carborundum cloth; in some cases this is too drastic, when gentle rubbing on a selvyt cloth may be tried; this procedure is, however, very slow. When the slice is of the requisite thinness, it is dried and covered with a cover-glass on which sufficient balsam has previously been cooked; this avoids warming the section more than necessary, and in this way the slide is completed.

"With very soft or plastic rocks, the use of a razor blade or even a microtome may prove more satisfactory than trying to grind down sections in the usual way."

Mounts other than with Canada Balsam.—The great advantage of mounting in Canada balsam is the refractive index standard it provides for subsequent optical determinations of the rock-minerals. This value (cooked balsam 1.538) approximates that of quartz, frequently used as the index-mineral of thickness (or required thinness) of section. There are cases, however, where it is not possible to use Canada balsam, especially if there is anything in the rock which easily fluxes with this medium on slight heat application (*e.g.* certain types of bitumen) or where, owing to the inherent nature of the rock, it is not possible to impregnate with balsam-shellac or synthetic resin (p. 42). Canada balsam solution in xylol or other solvent is unsatisfactory except for purely temporary mounts, since, when the solvent has evaporated, it takes a long time for the balsam to dry; in hot weather or tropical places, it may remain "tacky" indefinitely, to the discomfort both of the operator and microscope.

In difficult cases, air mounting may be resorted to, the slice having been dry or semi-wet ground previously, taken as thin as possible, thoroughly dried, thereafter transferred to a dry, clean and *thin* glass slip. The refractive index of air being 1, it follows that the normal R.I. standards of comparison of rock-minerals are completely altered. In point of fact, quartz (1.550) appears in strong relief in contrast to its normal demeanour in Canada balsam. Where a slice is air-mounted, the edges of the cover slip must be sealed either with wax or with solution of bitumen in benzol; this is done by painting round the cover slip with a fine camel-hair brush dipped in the solution.

Various forms of wax are also used successfully as mountants, from ordinary paraffin wax to specially prepared, so-called "Sira" wax, the latter useful where tenacity combined with a certain degree of plasticity is required.

Synthetic resins are applied more particularly to impregnating friable and porous rocks to enable them to be mounted with balsam; these resins are seldom used as mountants *per se*, though in special cases they may be appropriate. Their average R.I. is 1.62 (after heat treatment).

Pure rubber dissolved in xylene is sometimes used as a mounting medium in the microscopical examination of fine powders, *e.g.* pigments in the paint industry. It has a refractive index of 1.517 and forms a rigid bond, though it may not be optically clear.

As a temporary mounting medium, gelatine solution is much favoured in industrial microscopy, especially where extremely fine particles and colloidal materials tending to exhibit Brownian movement are involved.¹ Such a solution is prepared by dissolving 7 gm. of best emulsion gelatine in 100 ml. of distilled water to which 1 ml. carbolic acid solution is added (to prevent mould developing). When the gelatine is dissolved, a little albumen is added and the solution separated from the "foam," placed over a boiling water bath for half an hour and the clean gelatine then removed. The resulting solution is optically clear and can be used with advantage in many cases when investigating clay particles, fillers and the like.

W. Ahrens and H. Weyland² have recommended methylene methylethylketone as a mounting medium, the R.I. being 1.519 to 1.520.

Impregnating Friable and Porous Rocks—The Use of Synthetic Resin.—The essence of the use of resin for rock sections is its ability to be introduced in liquid form and thereafter by heat treatment converted to a hard solid without deforming or affecting the rock substance or structure in any way.

A. F. Hallimond employed this method in sectioning soft rocks such as clays and chamosite mudstones.³ C. S. Ross

¹ C. H. Butcher, *Ind. Chem.*, 9, 1933, p. 296.

² *Centr. j. Min.*, 1928, p. 370.

³ "Iron Ores:" etc., *Mem. Geol. Surv., Special Rep. Mineral Resources Great Britain*, 29, 1925, p. 37; also *Summary of Progress*, 1923 (1924), p. 144.

used "Bakelite" resin in a similar way for friable materials and has also described a method of surface treatment using either synthetic resin or a medium known as "Kollolith," a substance not unlike Canada balsam.¹ A. Scott Russell, in his work in connexion with stone preservation, developed special methods for sectioning disintegrated building stones in which specially prepared synthetic resin was employed.² M. Leggette³ has used "Bakelite" successfully with silts, clays, "bentonite" etc., to preserve original structures when grinding these rocks. R. J. Schaffer and P. Hirst⁴ investigated these processes in the course of research on weathering of building stones and their methods as developed at the Building Research Station (Department of Scientific and Industrial Research) are now generally followed in this country.

A dyed synthetic resin of the phenol formaldehyde type is employed with considerable success for all types of soft and friable rocks, building materials, cements, refractories and similar materials. Among the advantages of such resin over Canada balsam may be mentioned the following:—

(a) Rocks impregnated with resin will stand grinding much better than those mounted with balsam.

(b) Sections impregnated with resin do not "float" in the mounting process.

(c) Resin is easily dyed and when used in this form enables comparisons of porosities by detection of fissures to be very easily carried out.

A disadvantage attaching to the use of resin is that its refractive index, after baking, is approximately 1.62 as against 1.54 for cooked balsam and, therefore, the minerals in the slice mounted in resin have an abnormal appearance. With practice, however, this difficulty is soon overcome.

Two grades of resin are employed; a mixture of formaldehyde, phenol and m-cresol in the molecular proportions 6 : 3 : 3 is used for all normal purposes and a softer resin, prepared from a $5\frac{1}{2}$: 3 : 3 mix, for very friable specimens, particularly those which are badly weathered.

¹ *Amer. Journ. Sci.*, Ser. 5, vii, 1924, p. 483.

² "Report of the Stone Preservation Committee." London, 1927, p. 7.

³ *Journ. Geol.*, 36, 1928, p. 549.

⁴ *Proc. Geol. Assoc.*, 41, 1930, p. 32

The preparation of these resins is as follows. A round-bottomed flask of 1,000 ml. capacity is weighed and the requisite amount of phenol, m-cresol and formaldehyde added, the latter in the form of 40 per cent. solution. To catalyse the reaction, 1.5 ml. of ammonia (*s.g.* 0.880) are added for each 100 ml. of formaldehyde solution, after which the flask is closed with a double-bored cork through which a small mercury manometer and a tube closed with a stop-cock are inserted. The flask is heated on a steam bath for several hours until the mixture turns permanently cloudy and does not clear again on shaking. During this period, the pressure in the flask is maintained at approximately atmospheric by opening the stop-cock at intervals. The mixture is then run from the flask into a separating funnel and, when cold, the resinous layer is transferred to another 1,000 ml. round-bottomed flask. Safranine, amounting to 1/20th per cent. of the weight of the entire batch of resin, is added. For a paler colour, the amount of dye may be reduced. This resin is then dehydrated in vacuo at 20°C. to 30°C. until its refractive index reaches 1.590-1.591 for the 6:3:3 mixture and 1.596-1.597 for the 5½:3:3 mixture. Dehydration is carried out by connecting the flask through a T-piece with a mercury manometer and drying towers of calcium chloride and sulphuric acid. A three-way stop-cock is fitted between the flask and the first drying tower and enables the flask to be connected at will with the outside atmosphere. The last drying tower is connected with a vacuum pump and the apparatus evacuated to 12 mm. pressure, the flask containing the resin being immersed in water at 20°C. to 30°C. (*Fig. 3*).

Dehydration usually requires about 30 hours. If desired, the process may be stopped overnight, in which case air is admitted to the flask through the three-way tap before turning off the pump. This procedure avoids the possibility of sulphuric acid being forced back into the flask. Dehydration is considered to be complete when the refractive index of the resin as measured by a refractometer falls within the limits given above.

One of two processes is used for impregnation according to the nature of the work.

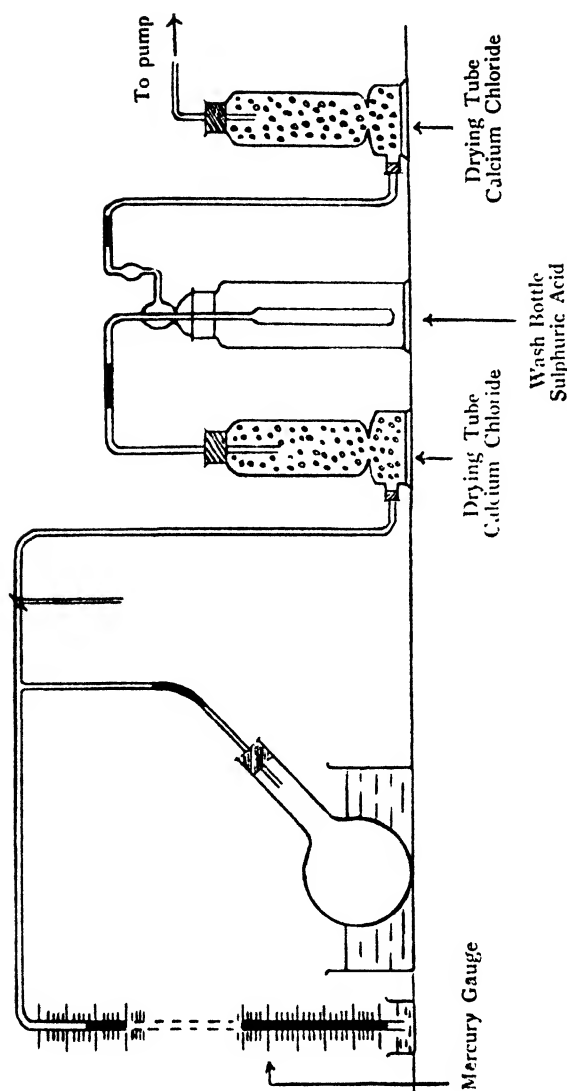


FIG. 3. Apparatus for Preparation of Synthetic Resin.

(a) *Surface Impregnation*.—This method will be found to be adequate for all but the most delicate work. Material prepared as described above may be used or certain commercial grades of resin are equally suitable. If the material described above is used with a solvent it should not be more than three weeks old. The section is cut to about $\frac{1}{8}$ in. in thickness and ground as flat as possible. It is then thoroughly dried and placed for a few minutes in an oven at 130°C . after which it is transferred to an electric hot plate, specially designed to give a uniform temperature of 115°C ., and the resin applied in thin layers until no more is absorbed. This procedure minimises the tendency to form air bubbles. The section is allowed to remain on the hot plate until it is quite hard while still hot, when it is taken off and ground on the medium and fine plates until the excess resin is just removed. The slice is then mounted in the normal manner except that, instead of placing it on the heated plate, it is warmed gently with a bunsen burner prior to laying it on the cooked balsam. In this way further contraction of the resin and dehydration of the material composing the slice is avoided. With comparatively non-porous materials, care must be taken not to grind too far as in such specimens the actual depth to which the section is impregnated is comparatively small. An alternative method which is very useful with some soft specimens is to apply the resin in the form of an alcoholic solution with a brush and repeat as often as necessary, afterwards baking it at a temperature not exceeding 90°C . In this case the lower baking temperature causes hardening to occur more slowly and diminishes the possibility of settling up strains in the resin as a result of contraction taking place on solidification.

With comparatively robust specimens the method followed at the author's laboratories is to place the slices in a small beaker and cover with an alcoholic solution containing 30-50 per cent. by weight of resin. The beaker is then gently warmed over a small flame until the bulk of the alcohol has evaporated and a viscous resin is left behind. During this process, the slices should occasionally be moved about with a glass rod to prevent them adhering to the bottom of the beaker. The amount of resin remaining at this stage should be more

than sufficient to cover the slices. The slices are then removed and baked at a temperature not exceeding 90°C. and the excess resin in the beaker diluted with alcohol and preserved for future use.

(b) *Thorough Impregnation.*—This process is reserved for the most friable rocks and the resin used should be freshly made, since after 24 hours it becomes too viscous to be used for thorough impregnation. It is most economical therefore to reserve samples for thorough impregnation until a number has been collected. The size of the specimen required varies according to its nature; 2 x 1 x 1 in. is suitable for very fragile materials, the edges of which have to be preserved, and 1 x 1 x $\frac{1}{4}$ in. for those which are more robust. A flat tray capable of holding sufficient resin to cover the samples makes a suitable container for the purpose. When the samples have been thoroughly dried, they are placed in the tray at the bottom of a vacuum desiccator. This is provided with a rubber hung in the centre of the lid through which a tap funnel and exhaust tube pass. Resin is placed in the tap funnel (the stop-cock of which should have a bore as wide as possible) and the desiccator evacuated to about 4 mm. pressure. The stop-cock is then turned and resin admitted directly into the tray containing the specimens until they are completely covered. After standing for half an hour, air is slowly re-admitted, the latter operation occupying 10-20 minutes. The baking process is carried out by heating for at least three hours at 40°-50°C. and then raising the temperature gradually to 70°-100°C., depending on the nature of the specimen. The time taken for the latter operation is usually about 48 hours.

Conventional Thickness of Rock-Sections.¹—In quartz-bearing rocks, this mineral is used as the index of thickness, which should be of the order of 30 microns revealed by the white, grey and pale yellow birefringence (1st order) colours between crossed nicols (p. 167). In the absence of quartz, feldspar may be taken as an indicator. In calcareous rocks, the section is taken as thin as possible, *i.e.* until the calcite is quite transparent in ordinary light or shows characteristic pinks and greens under crossed nicols. For a practical method of utilising birefringence as a diagnostic factor, see p. 168.

¹ See p. 167.

A convenient and inexpensive polarising apparatus for ascertaining the thickness of minerals during thin section grinding has been modified from a similar hand apparatus manufactured by Messrs. J. Swift and Son, Ltd., London, and has been successfully employed in the author's laboratories. The instrument is provided with both polariser and analyser, a single lens acting as an objective and a small swing mirror for transmitting light to supply the illuminating system. The instrument is mounted permanently on a vertical rod supported by a tripod and can be made to tilt to a convenient angle for observation, its position being secured by a thumbscrew.

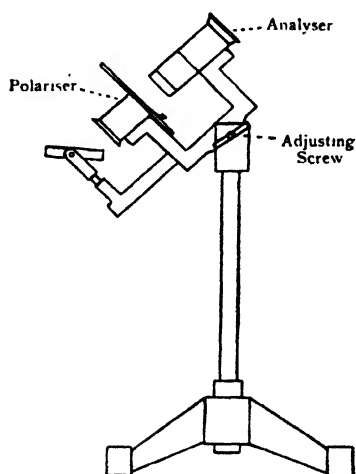


FIG. 4. Polarising Microscope.

A $3\frac{1}{2}$ in. stage fitted with clips to support the slide gives ample accommodation, while the focussing adjustment of the analyser tube is ample. The use of this apparatus obviates the necessity of having a more expensive petrological microscope in the actual rock-cutting room (*Fig. 4*).

Treatment of Incoherent Rocks for Recovery of Heavy Minerals, Micro-Organisms etc.

Although the principles are much the same in each case, the methods now to be described differ according to whether single separations of heavy minerals or micro-organisms are required from individual samples, or whether a large batch of samples (*e.g.* oil-well samples) is to be treated simultaneously for both forms of concentration. Methods for single separations are first discussed. Both panning and sieving may be necessary before proceeding with separations: see p. 65, 89.

At the outset, a schedule of essential equipment for this particular work may conveniently be given here:—

Iron Pestle and Mortar for crushing rocks, $8\frac{1}{2}$ in. diameter, bell-shaped, turned.

Sieves for ordinary use, in japanned tin frames, with cover and bottom, 6 in. diameter, 30, 60, 90 mesh.

Sieves for special quantitative work on material up to $\frac{1}{16}$ in. (2.057 mm.), B.S.I. test sieves, 8 in. diameter, with cover and bottom, 200,

100, 85, 52, 36, 25, 18, 7 mesh. (N.B.—These sieves can also be obtained of other mesh, but as they are expensive, a choice should be made which is suited to the work in view; the eight quoted above are those in most common use.)

Sieves for coarse materials: see full list of B.S.I. medium mesh test sieves and perforated plates, p. 88.

Evaporating dishes, 16 cm. wide, shallow, porcelain, for cleaning sediments.

Glass stirrers made from 5 mm. glass rod supplied in metre lengths by the 1 lb. weight.

Wire gauze, iron, with asbestos combined, cut in 5 x 5 in. squares for heating basins.

Tripod stands, 8 or 10 in. high according to size of burners used.

Sand-bath for drying acid-cleaned sediments.

24-Funnel-battery for heavy liquid separations (as Fig. 6, p. 64). Constructed of white wood or teak, $\frac{3}{4}$ or $\frac{5}{8}$ in. Overall length 4 ft. 6 in. width of base and shelves $10\frac{1}{2}$ in., each side $18\frac{1}{2}$ in. high, lower shelf $11\frac{1}{2}$ in. up from base, upper shelf $15\frac{1}{2}$ in. up from base, depth between shelves 4 in. Each shelf drilled with 24 holes, each 2 in. in diameter, one hole immediately behind the other, positions of holes in the lower shelf corresponding exactly with those in the upper shelf.

Retort stand for holding funnels etc., as Fig. 5, p. 53.

Funnels, white glass, short stem, 3 in. diameter.

Clock-glasses to cover funnels, $3\frac{1}{2}$ in. diameter.

Rubber tubing, black, $\frac{3}{8}$ in. diameter, supplied by the yard. $1\frac{1}{2}$ in. sufficient for each funnel.

Pinch-grips, for rubber tubing

Bottles, odd, coloured glass, for bromoform and solutions; also colourless for the funnel-battery, 24 to each.

Filter papers, Whatman No. 41, 11 cm. diameter, supplied in boxes of 100 circles; fan-folded patterns to order.

Hydrometer as specification, p. 51.

Wash bottle, 500 ml.

Hydrochloric acid commercial for cleaning, dilute 1 of acid with 4 of water.

Caustic soda, solid, for making N/10 solution.

Bromoform, 2.9 gravity, in 5 lb. coloured glass bottles carefully sealed and packed for export (where applicable).

Mercurous nitrate, 4.3 gravity as fused, in $\frac{1}{2}$ lb. bottles.

Benzol, pure, recrystallisable or 99 per cent. Industrial Methylated Spirits.

Methylene iodide, 3.3 gravity, in 4 oz. bottles (coloured).

N.B.—Other "heavy" liquids described on p. 70. See also schedule of equipment given on p. 36, items starred*.

For bromoform recovery from benzol etc., the following apparatus is desirable:—

Engler-type distillation flask, 500 ml. capacity.

Liebig condenser, glass body with inner tube fused in, 45 cm.

Condenser Stand, universal, with sliding rod and iron clamp.

Thermometer reading to 300° C.

Cork bored to take thermometer.

Wire gauze and tripod stand as above.

Single Heavy Mineral Separations.—The sample in the first place should be examined with a hand-lens for the detection of the larger and more easily identifiable minerals or micro-organisms and for those which may be destroyed by subsequent treatment with acid; such minerals as pyrite, limonite and glauconite, together with carbonates and most phosphates, are included in this category. A little material should also be mounted dry on a glass slip and examined under the binocular microscope, both by transmitted and incident light. Use a 36-mesh B.S. sieve to segregate coarser constituents and operate on all material which passes this sieve. [For discussion of sieving etc., see p. 89.]

The authigenic material coating sand grains if present is removed by gently boiling with water; often this suffices, but in many cases the addition of hydrochloric acid (1 : 4) is necessary to complete clarification, though with exceptionally ferruginous material, 1 : 1 hydrochloric acid may be necessary. It is, however, advisable to restrict as far as possible the quantity of acid used and also the time of digestion, since partial destruction of certain minerals is inevitable and in some cases total decomposition or solution may follow, as indicated above; loss from this cause is anticipated by the preliminary examination of the material as suggested. In the case of calcareous organisms, hydrochloric acid is obviously impracticable and the use of a strong potassium or sodium hydroxide solution is suggested. This alkaline digest is also applicable with advantage to sediments the limonitic content of which is not very great, though it takes longer time for clarification of the grains than the acid treatment; also to those cases where acid-soluble minerals are anticipated (as above). When the grains are clear they are washed free of acid or alkali with cold water and then dried slowly in a steam-oven or on a sand-bath.

The next operation involves the use of suitable "heavy" liquids for concentrating either the mineral particles having a specific gravity greater than the arbitrary standard of 2.90, or micro-organisms which, if of calcite, have a specific gravity of about 2.71 or silica particles of gravity 2.59-2.65. For heavy minerals, of the many liquids advocated and in use, the author favours bromoform (s.g. 2.88 to 2.90, varying considerably in

purity) for all general purposes. The objections, that it is liable to excessive convection current effects, rapid evaporation and that it is expensive to employ, may be met by certain preventive measures. These consist in carrying out the separation in a fume cupboard or constant temperature chamber, or in a room rendered free of air currents; also by keeping the bromoform covered when in use with a watch-glass which fits the funnel and taking care to preserve the benzol washings for the ultimate recovery of the bromoform dissolved; further, the price of bromoform cannot be regarded as prohibitive when compared with the prices of the various other liquids sometimes employed. In the hands of a careful manipulator, 1 lb. of bromoform should be ample for the separation of at least 50 samples, if care is taken to reduce loss to a minimum when recovering the liquid from benzol washings.

For calcite or calcareous organisms, dilute the bromoform with pure benzol (recrystallised) till the specific gravity of the solution is 2.69 (test with a hydrometer). A solution of s.g. 2.45-2.50 will be effective in differentiating quartz and/or calcite from gypsum: the former species sinks, the latter floats. Bromoform may thus be diluted to any strength, giving solutions of decreasing gravity and by this means specific minerals may be concentrated or diagnosed.

A type of hydrometer most suitable for checking the s.g. of bromoform and bromoform solutions is obtainable;¹ it embodies the following essential features:—

Length 20 cm.

Diameter of bulb 2 cm.

Range 2.6-3.0 (or other ranges as desired).

Scale graduated every 0.01 and made as long as possible so that graduations are clear.

Value 2.9 marked in red.

When testing the gravity of a solution, use a 500 ml. graduated glass vessel. Take care to insert the hydrometer cautiously; do not drop it into the liquid. In diluting bromoform, fill the vessel with sufficient liquid to float the hydrometer at 2.9, then carefully pour in benzol, stirring with a glass rod, until the desired gravity is registered. Both bromoform and bromoform solutions should be periodically checked for

¹ Messrs. T. O. Blake (Sikes Hydrometers), Ltd., 57, Hatton Garden, London, E.C.1.

specific gravity, stored in coloured glass bottles, kept out of sunlight and *kept cool* (if possible in an ice chest in hot countries). Deterioration is liable to be rapid if these precautions are not taken, especially if bromine starts to separate out. Should the liquid become badly discoloured, try shaking in a separating funnel with an aqueous solution of sodium hydroxide or an alcoholic solution of potassium hydroxide: the method may not be successful in bad cases of deterioration.

Redistillation is usually effective, but sometimes leads to a further settling out of bromine or hydrobromic acid. Recent trials employing a distillation under reduced pressure have, however, given successful results.

Recovery of bromoform from benzol-bromoform solution (or benzol "washings") is achieved by distillation, using an Engler-type flask, 500 ml. capacity and a Liebig condenser. Benzol boils at 80.5°C. and comes over first; bromoform boils at 151.2°C. ; it is advisable to keep an eye on the condenser at the higher temperature and stop the circulation of the cold water if large quantities of liquid are being distilled. S. Bracewell¹ advocates the use of methylated spirit instead of benzol for washing heavy mineral residues after bromoform separation. In this case the washings are poured into water; the methylated spirit dissolves and the bromoform can be drawn off and suitably dried. This method is followed in principle in the author's laboratories, employing 99 per cent. industrial methylated spirit. About 200 ml. of bromoform-alcohol washings are placed in a 2,000 ml. separating cylinder and about 1,500 ml. of water added and the mixture shaken. The bromoform separates to the bottom of the funnel where it may be run off and dried for re-use, unless, as sometimes happens in the separation of residues from bituminous rocks, it appears very dark in colour, in which case it is advisable to re-distil. Bromoform is not so readily soluble in alcohol as in benzol and for this reason washing requires to be carried out with care. An effective way of rapidly removing the bromoform is to direct a fine jet of alcohol on to the filter paper, using a wash bottle fitted with a rubber blow-ball.

In order to economise in the use of "heavy" liquid, take

¹ *Geol. Mag.*, 70, 1933, p. 192.

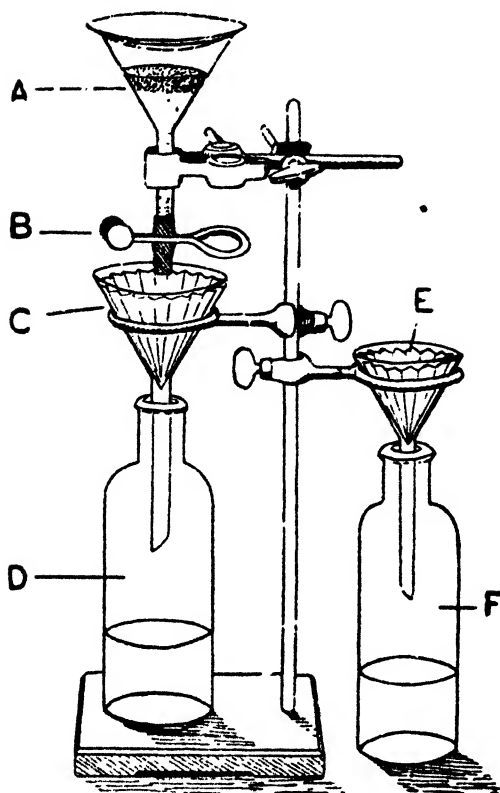


FIG. 5 Bromoform Separation Apparatus for Single Samples

- A. Funnel containing bromoform and sample from which heavy grains are settling down.
- B. Pinch-cock grip on rubber tubing attached to funnel stem.
- C. Folded filter paper for holding up residue.
- D. Bromoform bottle.
- E. Filter to prevent any solid material from entering F.
- F. Benzol (or other solvent) washings bottle.

the smallest amount of cleaned sample which is practicable. This implies from 10-15 gm. in the case of average silts (0.05 mm.- 0.1 mm. grade), 15-20 gm. of fine to medium sand (0.1 mm.- 0.5 mm.), 25 gm. of coarse sand (>0.5); coarse sands and gravels should be panned (the latter screened) to reduce bulk of material; the same applies to clays; see, however, p. 76.

A form of apparatus commonly employed for heavy mineral separations is shown in the accompanying diagram (*Fig. 5*) and is self-explanatory. The bottles used to hold bromoform and bromoform "washings" should be plainly labelled or "washings" may be accidentally added to the bottle containing bromoform. The sand is poured into the upper funnel and constantly stirred, at least half an hour being necessary to ensure a good separation. It is doubtful whether a 100 per cent. separation can ever be effected in practice, but with care it should be reasonably complete. Filtering may in some cases be accelerated by using fan-folded filter papers, obtainable from most makers. Both the light and heavy residues are washed free of bromoform with benzol and subsequently dried in a steam-oven or over a sand-bath. Other forms of separating apparatus, *e.g.* Spaeth, may commend themselves to the reader (*Fig. 7*, p. 73).

When dry, the residue may be further subjected to special treatment for specific mineral concentration, including magnetic separation and the employment of other "heavy" liquids or fused salts: see p. 70.

Heavy Residue Sampling.—It frequently happens that a heavy mineral residue obtained by bromoform or other separation is too large to be mounted on a single microscope slide. The problem of sampling has then to be faced. As G. H. Otto¹ points out, errors of sampling may be incurred through inability to produce the true conditions of random sampling or alternatively to factors which shift the "observed modal frequency of a component from its true value." Owing to difference in size, shape, density, magnetic properties, co-efficient of friction and elastic properties of grains, it is most unlikely that a truly representative sample can be obtained by means of a spatula.

Probably the simplest procedure in most cases is to place the heavy mineral residue on a sheet of glass and quarter it with a strip of stiff paper, continuing the process until a portion of the desired weight is obtained.

Attempts have been made to apply mechanical methods of

¹ "Comparative Tests of Several Methods of Sampling Heavy Mineral Concentrates." *Journ. Sed. Pet.*, 3, 1933, p. 30.

sampling relatively large masses to these residues, but usually without much success. W. C. Krumbein designed a conical hopper with a very small opening at the tip; this opening is placed over the intersection of two knife edges placed at right angles to each other. The sample when poured through the hopper is thus split into four portions, two of which are rejected and the other two passed through the hopper again and the process repeated until a suitably sized sample is obtained.

Where a sample of 25 gm. or more is required from a large quantity of material, the Jones ore sample splitter is frequently employed. This is fitted with a long narrow hopper into which the material is poured and divided equally into two pans by means of a series of inclined chutes. The material in one pan is passed through the hopper again and the process repeated until a sample of requisite size is procured.

This apparatus, however, is not suitable for very small samples, the chutes being constructed of folded sheets of iron. G. H. Otto designed a machine known as the "Microsplit" which is based on the same principle as the ore sample splitter, but which has for the inclined chutes a series of 16 brass plates each $1/16$ in. thick with polished inclined edges. Thin bronze partitions separate the plates and the parts are held together by screws after pressure in a strong vice. It is claimed for this device that it is far better than using a spatula or pouring a few grains from a vial and results certainly seem to support this contention. Moreover, it is very quick in operation.

C. K. Wentworth, W. L. Wilgins and H. L. Koch¹ later described two rotary sample splitters, one for large samples of coarse material and the other for small samples of heavy minerals, but each of similar design.

The mega-splitter embodies a ply-wood turntable mounted on a vertical steel axle the hardened points of which pivot in adjustable centre screws. In a circle concentric with the axle are mounted sixteen 4 oz. metal pill boxes and a funnel is arranged directly over this circle so that on rotation the boxes pass in turn under the funnel. The axle is spun by hand and the rate of turning can thus be adjusted as required. The sixteen original samples may be used or, by combining opposite

¹ "A Rotary Type of Sample Splitter." *Journ. Sed. Pet.*, 4, 1934, p. 127.

sixteenths, eighths can be formed; similarly quarters by taking each fourth sixteenth or halves by taking alternate sixteenths, may be formed. By halving in this way and successive repetition of the procedure the desired fraction can be obtained.

The micro-splitter is similar in design but is fitted with 16 small glass vials in place of the metal pill boxes. Difficulty is experienced with very small samples in producing a slow, steady stream of mineral grains, but is overcome by mounting a small piece of glass tubing on a pair of trundle rollers driven by a rubber band belt from a small hand crank. The turntable is rotated from the same crank by another belt. A small funnel with an elongated outlet is used to reduce loss of grains by bouncing on the edges of the moving vials. Tests of these machines show that more accurate results are thus obtained than with other known sample splitters.

Mounting of Sand Grains for Microscopical Examination.—The final operation consists in mounting the residue or concentrated material with Canada balsam on a glass slip and is similar in many respects to the technique described for thin sections (p. 37), except that it is a little more difficult to attain complete expulsion of air-bubbles. It is advisable wherever possible to mount the total residue for microscopical examination; by so doing, risk of losing rare species is minimised. The different magnetic crops, if isolated (p. 126), are mounted separately and a representative sample of the light material may also be mounted. Glass microscope slips (3×1 in.) and thin cover-glasses ($1\frac{1}{4} \times \frac{7}{8}$ in. or $\frac{7}{8}$ in. square) are the most useful sizes. Non-permanent mounts may be made by using ordinary cedar oil, R.I. 1.516; or air-mounts, especially of micro-organisms, may be preferred.

The exclusion of air-bubbles has been mentioned. This process is aided by moistening the cover-glass with turpentine or xylol before pressing it down on to the slip; this may be varied by putting the grains on to the moistened cover-glass and then pressing it down on to the slip on which the balsam is sufficiently heated. A little careful "to-and-fro" motion imparted to the cover-glass with tweezers, while the balsam is still hot, is often all that is necessary to obviate the presence of such bubbles.

Solution of the surplus balsam is rapidly obtained as before (p. 39) by using methylated spirit or benzol, a final immersion of the slide in ether being advantageous, but not necessary. Xylol is probably the quickest solvent, but it has an unfortunate habit of eating into the balsam under the cover-glass and thus impairing the mount.

With minerals or rock-fragments capable of passing through a 36-mesh B.S. sieve, little difficulty, save with air-bubbles, is experienced in mounting with Canada balsam, but with larger material (+36), unless an inordinate thickness of balsam is used, the method is not practicable. Some workers employ satisfactorily vulcanite rings cemented either by a special gum or with balsam to the slide; more balsam is then put into the ring, together with the material to be mounted and when cooked, a circular cover-glass is affixed; this is an old method, but one which with care is quite satisfactory, though uncooked or too highly coloured balsam, or air-bubbles, may be troublesome. Another method is to employ microscope slips in which a shallow, bowl-shaped hollow has been ground on one surface; such slips are very useful for air-mounts of *foraminifera*.

A. W. Slocum and E. T. Thomas¹ have devised a neat form of mount which is very useful for micro-organisms and large mineral grains. It consists of a celluloid strip 24 x 60 mm. (of thickness to suit the material) punched at regular intervals by means of an ordinary paper punch giving about 4 mm. holes. The celluloid strip is then cemented to an ordinary glass slip with acetone. Each "cup" thus prepared will receive a grain or organism, which may be cemented in any particular position (if desired), or may be left free as an air-mount. A thin cover-glass, of same length and breadth as the strip, is then cemented on to it with acetone, thus completing the mount. The value of this mount lies in the possibility of preserving on one slide characteristic mineral grains of a peculiar assemblage or representative micro-organisms from a particular horizon etc.

Where a black background is preferred, as is often the case with coloured minerals or *foraminifera*, a similar slide can be

¹ *Bull. Amer. Assoc. Petrol. Geol.*, 9, 1925, p. 667.

made of cardboard suitably punched and glued on to a piece of thin black cardboard of identical size, as described by G. D. Hanna and H. L. Driver.¹ From the point of view of permanence, however, the celluloid-glass combination has much to recommend it.

A. C. Tester² utilises a novel method of mounting *foraminifera*, other small organisms or heavy mineral grains. Ordinary cardboard slides with a cut-out are employed with a thin cover glass at the bottom of the cut-out to produce a stronger light effect on the under side of the mineral grains. A strip of cellophane is then fixed with cement or glue to the top of the slide. To effect the cellophane covering, a thin strip about $\frac{1}{4}$ in. wider than the opening of the slide is cut and the ends twined over and cemented on the under side of the slide. A smooth and dust-proof cover results if sufficient care is taken to pull the cellophane strip taut. The advantages of cellophane over a thin cover glass are numerous. The slide does not break if dropped, it can be pressed in handling and generally submitted to rougher treatment. Further, cellophane is about $\frac{1}{5}$ th the thickness of an average cover glass, which is advantageous when high power objectives are employed; if the objective touches the slide, the cover slip of cellophane yields slightly but does not break; neither does it scratch the objective as a glass slip is liable to under pressure.

Systematic Procedure for Simultaneous Investigation of Samples for Micro-Organisms and Heavy Minerals.—The extended use of petrological and micropalæontological methods of subsurface correlation in the principal oilfields of the world during the last few years has compelled the development of a special technique for handling simultaneously several samples rather than single specimens, as has been customary in the past. This technique, while differing in detail according to local circumstances and demands, is, in its broader outlines, applicable to all large-scale operations of this description, whether of academic or economic purpose. With increased facilities for obtaining rock-samples under practically all con-

¹ "The Study of Subsurface Formations in California Oilfield Development."
10th Ann. Rep. Calif. State Min. Bur., 10, 1924, No. 3, p. 5.

² *Journ. Sed. Pet.*, 2, 1932, p. 125.

ditions of exploratory work, improved methods of preparation and analysis have evolved collaterally, so that the fullest possible stratigraphical evidence may be elucidated from a series of samples with the minimum of time and preliminary treatment.

Apart from the special manipulation of samples for their heavy minerals as a basis of petrographic methods of correlation, the work of palæontologists on the micro-organic contents of such samples (including the *foraminifera*, *diatomacea*, *bryozoa*, *radiolaria* etc.) as standardised by the geological staffs of oil companies operating in Texas, Louisiana, California and elsewhere, has had a marked effect on the trend of organisation of laboratory work for the exhaustive investigation of well-samples. The most detailed, hence the most valuable, *subsurface* stratigraphical evidence to be obtained from any kind of sedimentary rock is that which is compounded of palæontology and petrology; correlation based on one or the other may be entirely satisfactory as a practical expedient and limited to local conditions; correlation based on the cumulative evidence of both lines of investigation carries with it the support of strong scientific probability and is accordingly more exact and certainly of greater consequence.

Such comprehensive analysis of sedimentary rocks represents the ideal to which all relevant research should tend, though for obvious reasons its attainment is largely restricted to those spheres of oilfield activity where highly trained technical staffs enjoy full laboratory facilities for the prosecution of such work: with a more general appreciation of the principles and methods involved, however, it is certain that they will be more widely adopted, not only under oilfield conditions, but equally in all phases of sedimentary petrological research.

Pursuing each line of investigation exclusively implies independent treatment of separate portions of a sample for its heavy minerals and its micro-fossils, a duplication of preparatory work which is an unnecessary waste of time. The development of a systematic procedure for simultaneous extraction of both constituents became, therefore, a desideratum, especially in large-scale work and a few attempts to formulate such a plan were made by American workers with varying

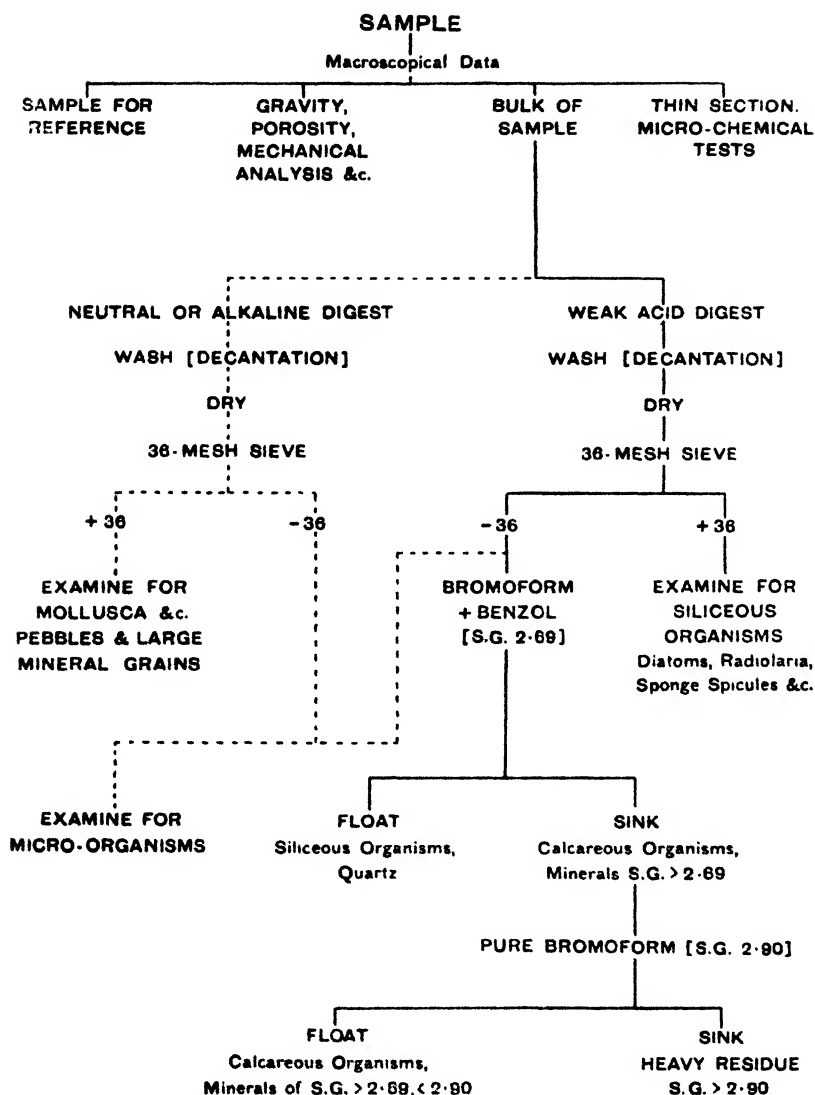
degrees of success, in particular that devised by G. D. Hanna and H. L. Driver.¹

Experience with all kinds of rocks, surface samples, oil-well samples, cores, "cuttings" and the like; has resulted in the adoption by the author of the procedure detailed in the following paragraphs. This plan of operation has the advantage that, although it makes for routine practice which can be carried out by non-technical assistants under supervision, it is sufficiently elastic at critical stages to be adaptable to special circumstances which may arise during the course of investigations. The ultimate success of this procedure depends to some extent, however, on the initial measures adopted for classifying the samples, not only as a basis of their comprehensive analyses, but also for purposes of collateral and future reference; accordingly some system, such as that already described for filing information (p. 25), is an essential preliminary to this technique.

Before proceeding with the treatment of the samples, the batch should be arranged in definite order; they should not be selected indiscriminately. With samples derived from the same oil-well, the series should be made up in ascending or descending order according to depth, the deepest being taken first and working gradually upwards to those nearer the surface, or *vice versa*; where investigations are proceeding collaterally with the drilling of the well, as is often the case, obviously the reverse order will be maintained, each batch of samples being dealt with in order of depth as they are received from the well. With outcrop samples some similar system should be adopted, implying a geographical sequence, e.g. direction of traverse, strike direction, vertical sequence (quarry-face, cliff-section etc.), stratigraphical sequence and so on. The advantage of such orderly procedure will readily be appreciated when the treatment of a series of related samples is contemplated, since connected results automatically emerge as the work progresses.

The "flow-sheet" (p. 61) shows in concise form the plan of procedure. Where only heavy mineral concentrates are sought, the standard methods of separation previously described

¹ *Op. cit.*



hold good, though modifications in apparatus for dealing with a number of samples at the same time are noted below (p. 64). Where organisms only are required and where it is desired to segregate calcareous and siliceous forms, the procedure need only be followed as far as the bromoform-benzol stage, though final treatment with bromoform to get rid of heavy minerals, especially if much pyrite occurs (p. 75), is often advantageous. Samples which are impregnated with petroleum residues require special treatment at the outset (p. 68).

Macroscopical Data. (See also p. 31). In the first instance the sample is spread out on white paper or in a large shallow evaporating basin for macroscopical examination, aided by hand-lens. A record is then made of the colour, lithological nature, pebble constituents and shell-fragments (if any) etc., which may be apparent. Approximately three-quarters of the sample is then taken to constitute the "bulk-sample"; the remaining quarter is divided into a portion for reference ("key-sample"); a portion for physical tests if desired (e.g. specific gravity, porosity, mechanical analysis) and, if required and practicable, a suitable piece is selected for thin section preparation which, apart from the microscopical examination in the usual way, can subsequently be utilised for any particular micro-chemical tests; in the case of physical tests, where these are of paramount importance, probably more than the suggested amount (25 per cent.) of the original sample will be utilised: it depends largely on the quantity of the sample initially available.¹

With core-samples and compact rocks such as shales, mudstones etc., it is necessary to break these down: before proceeding, bearing in mind, in the case of core-samples, the precautions already noted (p. 21). Such disintegration can generally be accomplished by splitting the material parallel to any prevalent lamination or bedding and then crumbling the laminæ or fragments thus obtained with the fingers or with the aid of a pestle and mortar; drastic pulverisation is to be avoided wherever possible. In refractory cases, several methods have been devised to promote disintegration; heating the sample to redness and then plunging into cold water is one common method; other methods consist in boiling the fragments with caustic soda; in covering the crushed sample with an equal amount of sodium acetate, adding a few drops of water and heating, when the crystals melt; the sample becomes saturated with the solution and on cooling the addition of a crystal of the acetate causes crystallisation; the force thus exerted determines the disintegration of the rock particles;² a similar result can be achieved by the use of sodium thiosulphate.³ An application of A. Mann's method⁴ of disintegrating diatomaceous shales also suggests itself: this consists in boiling the fragments for a few moments with sodium carbonate solution and then quenching with hydrochloric acid; the evolution of carbon dioxide has the effect of breaking down the shale successfully.

¹ For relevant methods and calculations, A. Holmes' "Petrographic Methods." (Murby, London), 1921, Chapters 2 and 5, should be consulted.

² M. Guinard, *Journ. Queckett Micros. Club*, 1888, Ser. 2, iii, p. 188.

³ G. D. Hanna and H. L. Driver, *op. cit.*, p. 14.

⁴ A. Mann, *Proc. U.S. National Mus.*, 60, 1922, p. 1.

"Bulk-Sample." The "bulk-sample" is divided into two portions, one digested with weak hydrochloric acid (1:4 or weaker): "acid digest"; the other is treated with caustic soda: "alkaline digest." If known to be rich in calcareous organisms, treat the major part of the sample with alkali. In both cases gentle though possibly prolonged heating accomplishes clarification and in the case of the acid, removal of soluble minerals and calcareous organisms which, however, are preserved in the alkaline digest.

Acid Digest. The authigenic material, mud or scum resulting from this digestion is washed away with cold water by decantation, the remaining portion being dried over a sand-bath or in a steam-oven. When dry and cold, it is passed through a 36-mesh sieve; the +36 material is examined carefully for the larger siliceous organisms (diatoms, *radiolaria*, sponge spicules etc.), significant rock-fragments, pebbles or mineral grains; large constituents are picked out by hand or with tweezers, the smaller organisms etc., with a camel-hair brush moistened with glycerine or cedarwood oil, usually under a strong hand-lens. All or a portion of the -36 material, depending on the quantity, is next transferred to the bromoform-benzol solution of specific gravity 2.68-2.70. This solution serves to float off the smaller siliceous organisms and the light minerals (including quartz) of specific gravity <2.68-2.70. The material which sinks is the heavy mineral residue plus any calcareous organisms which may have escaped destruction by the acid treatment. The light and heavy fractions are dried.

Alkaline Digest. The alkaline treatment serves to clarify the other portion of the "bulk-sample" and aid the detection of calcareous organisms; incidentally, it helps in disintegrating the particles if there has previously been some difficulty in doing this. The scum is again washed off by decantation, taking care not to lose anything but the muddy matter and the residue dried over a sand-bath as before. It is then passed through a 36-mesh sieve; the +36 material is segregated and examined for the more prominent pebble constituents, large mineral grains, molluscan or other fossil organisms which may be separated by hand as with the similar product from the acid digest. The -36 material is next added to the -36 material from the acid digest and the whole passed into the bromoform-benzol solution; or, if preferred for any particular reason, the bromoform-benzol concentration may be carried out separately on both lots. As explained above, this solution has the effect of floating off the light minerals (quartz) and the siliceous organisms which can thus easily be concentrated; calcareous organisms, preserved by the alkaline digest, are left behind with the normal heavy mineral suite. Some difficulty may be experienced at this stage in getting the calcareous organisms to sink completely if, in the case of *foraminifera*, the previous treatment has resulted in the cells filling up with air; this can be overcome to a large extent by very complete stirring and by constantly depressing the material with a glass rod well into the solution.

Bromoform Separation. The last stage in the process consists of floating off with bromoform (s.g. 2.9) the calcareous organisms (*foraminifera* particularly) and minerals of specific gravity >2.68-2.70 and <2.9 from the ultimate heavy mineral residue (>2.9) used in petrographic methods of correlation. Thus a microscope slide of the "light" material will consist principally of a concentrate of calcareous organisms minus quartz, the desired end in view, since it saves the necessity of tedious hand-picking of minute bodies under the microscope.

Simultaneous separation of at least two dozen concentrates (either

with the bromoform-benzol solution or with bromoform alone) is achieved by the use of a funnel-battery capable of holding 24 funnels with corresponding drainers as shown in Fig. 6. Two of these batteries side by side are employed, one for the bromoform-benzol separations, the other for the normal bromoform separations, the concentrates being passed on from the first to the second automatically. Those accustomed to carrying out single bromoform separations will readily appreciate the great saving of time and labour afforded by such large-scale operations. It may be argued that bromoform is expensive to use in this way, but 2 lbs. of the liquid will be ample to fill 24 funnels with an adequate amount, and ultimate loss through volatilisation is not much greater, if care be taken, than when using the same amount for successive single separations; also, the use of bromoform on this scale adds considerably to the quantity of bromoform washings (in benzol) at any one time, so that it pays to redistil the washings for recovery of the heavy liquid at the end of a day's run. The supervision of two of these funnel-batteries in simultaneous operation renders it possible to dispose of well over one hundred samples in a comparatively short time.

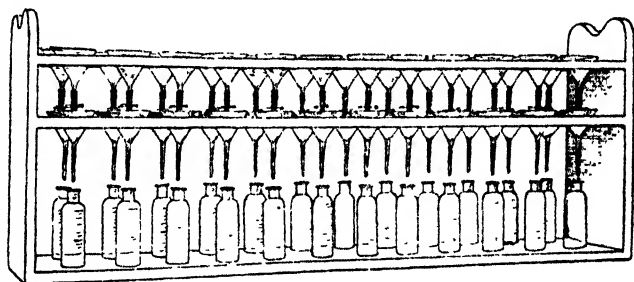


FIG. 6. Funnel-battery for Bromoform Separation.

At first glance the foregoing procedure may seem somewhat complicated, but a trial will prove its efficacy and comparative simplicity of operation. It is not contended that the plan is an infallible one or that cases do not arise where certain departures from the routine may be desirable; but where separate concentrations of groups of organisms and heavy minerals are required from a number of samples with some degree of rapidity, the procedure has much to commend it. Its success is more readily assured by having the requisite apparatus always handy, keeping special dishes, sieves etc., apart for the two different digests; apparatus used for the alkaline treatment may conveniently be designated with a blue mark on each article, that for the acid digest, with a red mark; in this way confusion of products is avoided during operations.

The acid and alkaline solutions should be made up ready in Winchester Quart bottles and suitably labelled; sufficient bromoform-benzol solution should be made up for one batch of samples at a time and not in too great a bulk, since it is liable to deteriorate on keeping, as already mentioned (p. 52). The real secret of successful work on these lines lies in the establishment of the necessary organisation, including equipment, under which the several operations can be carried on uninterruptedly; shortage of apparatus, intermittent attention, incorrect solutions (as regards gravity), or, what is worse, inability to "keep one's head," are one and all certain causes of failure.

Special Methods of Concentration.—Panning.—Where the initial bulk of a sample is greater than that desired for heavy mineral analysis, it may be conveniently reduced by the ordinary process of panning under running water in a wide, open tray, developing dish or evaporating basin. The secret of success here lies in the ability to give a combined circular and "to-and-fro" motion to the water; this has the effect of swirling out the lighter and finer constituents, which are carefully poured off and concentrating the larger and heavier grains. Skilful panning should not result in any appreciable loss of heavy mineral.

Exactly the same process is carried out when operating on fine grained rocks, *e.g.* clays, shales etc., and crushed rocks (p. 80). It has also been used with some degree of success in cases where heavy liquids have not been available for mineral concentration.

In the matter of panning as preliminary to heavy mineral concentration, certain warning is necessary to those without experience of this procedure. C. J. Ewing¹ has pointed out that the two most common methods of heavy mineral separation adopted (bromoform separation and panning in water) imply apparatus and technique which are by no means standard; further, many investigators carry out preliminary panning of the material prior to separation by bromoform. Vastly different results, he maintains, are achieved with

¹ "A Comparison of the Methods of Heavy Mineral Separation." *Geol. Mag.*, 68, 1931, p. 136

material which has been subjected to preliminary panning and material which has been subjected to bromoform separation alone and he gives convincing data in support of this claim. His procedure briefly was as follows:—In each case four 10 gm. samples were taken, of which the first and third were subjected to panning and the second and fourth to direct bromoform separation. A "steep sided" 9 in. evaporating dish was used for panning with no inward groove at the edge. Usually only one panning was deemed necessary, but in some cases samples were panned three times as a check. The residue from panning in each case lay between 5 and 10 per cent. by weight of the original sample. After drying this residue was passed through bromoform. The whole of the residue was then mounted. To expedite the work of counting, a system of keys, each one operating a "Veeder Counter" was employed.

Omitting opaque minerals, the species counted were zircon, rutile, staurolite, kyanite and tourmaline, but actually results were only considered representative for zircon, staurolite and tourmaline. Comparison of ratios between panned and non-panned materials shows a consistent excess of zircon in panned results, close similarity in the figures for staurolite and a consistent loss in panning in the case of tourmaline.

Retention of heavy grains in the "light" crop was probably attributed to "size of grains, density, surface tension and the time factor." Zircon, which has an average diameter of 0.1 mm., thus fills the interstices between the larger quartz grains and impedes sinking. Tourmaline having only a slightly greater density than bromoform and also being found in "flat faced" grains causes partial exclusion from the heavy fraction.

If an indefinite time were taken over the separation and constant stirring employed, each grain would obviously ultimately make its way to the clear bromoform. For an ideal separation the quartz layer should only be one grain thick when practically no obstruction could occur. The personal factor also enters largely into the problem of panning as frequently grains are lost during the process.

Probably the best way of achieving a uniform method of separation is by a compromise between panning and bromo-

form separation. The loss of minerals would not be great if panning were used to reduce the bulk to one half, as it is in the final stages that the greatest loss occurs. The samples after drying could be passed through bromoform in the usual way and the absence of much quartz at this stage would prevent obstruction of grains in their way to the clear bromoform.

Centrifuge Methods.—Workers on sediments are all familiar with the difficulties of extracting reasonable heavy residues from the finest grades such as clays, suspensions in asphalt, limestones etc. In fact, in some cases ordinary bromoform or other heavy liquid method, owing to surface tension or other effect, is quite inadmissible. The first apparently to apply centrifugal methods was F. von Wolff,¹ who used acetylene tetrabromide or Clerici's solution (p. 72) in a special form of sling-tube; by suitably heating the centrifuge he was able to employ successfully fused salt diluted with silver nitrate for minerals of higher specific gravity than 4.2. I. C. Brown² developed a special quantitative method of separating heavy minerals with bromoform, by suitably modifying the normal type of centrifuge tube in fixing to it a small cylindrical glass container to catch the minerals when thrown down. F. Schroeder³ and W. Kunitz⁴ have worked on similar lines with specially shaped sling-tubes.

The method for some time past employed in the author's laboratories was developed particularly to deal with heavy minerals from (1) fine sediment in native asphalts or bituminous rocks irrecoverable by any other means; (2) rock powders (*e.g.* limestone) containing a very small amount of heavy residue and (3) sediment of a type where grain size is small and therefore rate of sedimentation of particles in bromoform low. As this technique is quite simple to employ, does not call for expensive equipment and is equally applicable to all sediments or

¹ "Die Trennung fester Phasen durch die Zentrifuge." *Centr. j. Min., A*, 1927, p. 449.

² "A Method for the Separation of Heavy Minerals of Fine Soil." *Journ. Paleont.*, 3, 1929, p. 412.

³ "Scheidetrichter zum Einsetzen in die Zentrifuge beim Trennen von Mineralgemischen mit schweren Flüssigkeiten." *Centr. j. Min., A*, 1930, p. 38.

⁴ "Eine Schnellmethode der gravimetrischen Phasenanalyse mittels der Zentrifuge." *Centr. j. Min., A*, 1931, p. 225.

crushed rocks, particularly for heavy mineral extraction, a full account is given here.

With bituminous impregnated rocks special initial preparation must be undertaken to obtain satisfactory heavy residues. In the first place the impregnating bitumen must be extracted as completely as possible before any attempt is made to recover heavy minerals. The best way of effecting this is to take at least a 100 gm. sample and employ the method described on p. 193 for the determination of soluble bitumen. After drying the residual mineral matter in an oven, it is removed from the filter paper and treated with cold 6N hydrochloric acid until effervescence ceases. Care is taken to avoid undue excess of acid. The liquid is then filtered through a Buchner funnel, the residue being washed with water and dried in an oven.

One to five gm. of the insoluble matter are placed in a centrifuge tube about 4 in. long and $\frac{3}{4}$ in. in diameter and 10 ml. of bromoform added, the mixture being stirred to ensure that the powder is completely wetted. The tube is then placed in a centrifuge and whirled for half to one minute. A small hand-driven machine capable of about 1,500 r.p.m. is quite satisfactory for this purpose as it is not desirable to employ a very high speed of rotation.

The light residue forms a cake on the surface of the bromoform and can be removed almost completely with a spatula without disturbing the remainder of the solution. The tube is then rapidly inverted over a beaker and held in an inverted vertical position whilst any light residue adhering to the sides of the tube is wiped away with the finger. The heavy residue adheres to the bottom of the tube and can later be washed out with methylated spirit. It is essential to keep the centrifuge tube in an inverted position whilst removing the last traces of light residue, otherwise the latter may run down and contaminate the heavy residue.

When the sides of the tube are clean, the heavy residue is washed out with methylated spirit on to a watch glass and the excess of liquid poured off. In some cases, the residue may now be clean enough to mount, but usually the grains are contaminated with carbonaceous matter which interferes with subsequent identification of the minerals. One of the most satis-

factory methods of cleaning the residue is to treat it with 1 or 2 ml. of 100 vol. hydrogen peroxide and warm on the steam-bath until oxygen begins to be evolved. The watch glass is then removed and the liquid stirred until the reaction ceases, when dilute hydrochloric acid is added and the mixture allowed to stand for a short while. The excess of acid is poured off and the residue carefully washed, first with water and then with alcohol and dried, when it is ready for mounting. This treatment naturally removes a considerable amount of pyrite (if present) and cannot be adopted in all cases. Alternative cleaning agents are chloric acid or dilute nitric acid to which a few drops of alcohol are added.

For preparation of heavy residues from the acid-washed material removed from a mastic asphalt, a 2 gm. sample is ample and it is usually a definite disadvantage to take more. If a greater quantity of heavy residue is required, it is better to centrifuge in two separate portions. For sands and other coarse rock powders, it may be necessary to take up to 5 gm.

C. B. Claypool and W. V. Howard¹ have used a special technique, involving heavy liquid separation with a centrifuge, applicable to *calcareous* oil-well cuttings, essentially to determine the relative quantities of calcite and dolomite in such samples. The heavy liquid employed is mercuric potassium iodide (Thoulet's solution). Their procedure is as follows:—

Two ml. of the sample ground to pass an 80-mesh sieve are placed in a 15 ml. graduated centrifuge tube. Approximately 10 ml. of the heavy liquid diluted to a density of 2.75 are added and the whole mixed thoroughly by means of a glass rod and shaking. The mixture is then centrifuged for 3 to 5 minutes at about 700 r.p.m. The light fraction, or floating material, is then poured off into another tube. If separation is incomplete, the operation may have to be performed twice. The light fraction is then re-centrifuged to remove any heavy material which may be present, decanted and sufficient water added to sink it all. It is again centrifuged and all the liquid poured off. A volume determination of the light fraction is then made.

¹ "Method of Examining Well-Cuttings." *Bull. Amer. Assoc. Petrol. Geol.*, 12, 1928, p. 1147.

Hydrochloric acid is slowly added to the measured fraction until effervescence ceases. The insoluble residue is centrifuged for about 3 minutes and the volume of sand and shale fractions determined directly. The volume of calcite is calculated by difference.

The medium fractions are then all collected together and centrifuged in the undiluted heavy liquid (density 3.05). The solution and that portion of the sample which floats is subsequently poured off, leaving the heavy fraction as residue. Water is added as in the case of the light fraction and the liquid decanted after centrifuging. The volume of the medium fraction having been determined, concentrated hydrochloric acid with a little nitric acid is added until effervescence ceases when heated on a water bath. The residue is then centrifuged and the volume of dolomite calculated by difference.

The heavy fraction obtained during the above procedure is mixed with water to dissolve any iodides which may have crystallised out. Its volume is then measured and the same procedure with hydrochloric and nitric acids followed as for the medium fraction. Magnesite can then be calculated by difference.

Results obtained with this technique show a high order of accuracy as compared with those obtained by examination of large fragments stained with Lemberg's solution. In each case, however, the insoluble fraction recorded is larger than that calculated from analyses. This is due to the fact that during the course of analysis finer grinding is employed and complete separation of insoluble from soluble material achieved by frequent evaporation to dryness. It would not, however, be practicable to grind the material finer than to 80 mesh for the centrifuge method owing to the difficulty of sinking very fine grains in water. The margin of error is never, in any case, of detriment to final results.

Heavy Liquids and Substances other than Bromoform for Mineral Separation.—If it is desired to segregate a particular mineral or suite of minerals from (generally) an initial bromoform residue, apart from methods detailed in Chapter V, use may be made of different liquids and/or fused salts or mixtures. The following is a list of some of the more

important media which have been described and used:—
1, 2, 3, 4, 5, 6, 7.

Acetylene tetrabromide.	S.G. 1.6 — 2.95. <i>Dil.</i> chloroform or benzene.
Antimony tribromide.	S.G. 3.11 — 3.65. M.P. 94.2°C. <i>Dil.</i> water.
Antimony trichloride.	S.G. 2.59 at 100° C., 3.06 at 26°C. <i>Dil.</i> water.
Arsenic tri-iodide plus antimony iodide in solution of arsenic tribromide and methylene iodide.	S.G. 3.70 at 20°C.
Barium bromomercurate.	S.G. 3.11 at 11°C., 3.14 at 18°C
Barium mercuric nitrate.	S.G. 3.59. (Rohrbach's solution).
Cadmium borotungstate.	S.G. 3.36. <i>Dil.</i> water. Remove carbonates before separation with this compound.
Carbon tetrachloride.	S.G. 1.58 — 1.61.
Lead chloride.	S.G. 5.0.
Lead tetrabromide.	S.G. 3.5.
Lead tetrachloride.	S.G. 3.18 (0°C.). M.P. —15°C. Decomposes violently at 105°C., avoid heating.
Lead-zinc chloride.	Melt together in all proportions to give compounds of varying S.G.
Mercuric nitrate.	S.G. 3.3 — 3.4.
Mercuric potassium iodide.	S.G. 3.18. Keep mercury in bottle. Attacks rubber.

¹ E. Clerici, "Preparazione di liquidi per la separazione dei minerali." *Rend. R. Acad. Lincei*, ser. 5, 16, 1907, p. 187.

² J. W. Retger, "Ueber schwere Flussigkeiten zur Trennung von Mineralien." *N.J.J. Min.*, 11, 1889, p. 185.

"Die Bestimmung des specifischen Gewichte von in Wasser löslicher Salzen." III. "Die Darstellung neuer schwerer Flussigkeiten." *Zeitschr. f. physik. Chem.*, 11, 1893, p. 328.

"Thalliumsilbernitrat als schwere Schmelze zu Mineraltrennungen." *N.J.J. Min.*, 1, 1893, p. 90.

"Versuche zur Darstellung neuer Schwerer Flussigkeiten zur Mineraltrennung." I. "Die Acetate der Schwermetalle als schwere Schmelzen." *N.J.J. Min.*, 1, 1896, p. 212.

"Versuche zur Darstellung neuer Schwerer Flussigkeiten zur Mineraltrennung." II. "Die Nitrate und Doppelnitrate der Schwermetalle als schwere Schmelzen." *N.J.J. Min.*, 11, 1896, p. 183.

³ C. Rohrbach, "Ueber die Verwendbarkeit einer Bariumquecksilberjodidlösung an petrographischen Zwecken." *N.J.J. Min.*, 11, 1883, p. 186.

⁴ E. Sonstadt, "Note on a new method of taking specific gravities, adapted for special cases." *Chem. News*, 29, 1874, p. 127.

⁵ J. D. Sullivan, "Heavy Liquids for Mineralogical Analyses." *U.S. Bur. Mines. Tech. Paper* 381, 1927.

⁶ J. Thoulet, "Note sur un nouveau procédé d'étude au microscope des minéraux en grains très-fins." *Bull. Soc. Min. France*, 11, 1879, p. 188.

⁷ H. E. Vassar, "Clerici solution for mineral separation by gravity." *Amer. Min.*, 10, 1925, p. 123.

Mercurous nitrate.	S.G. 4.3. M.P. 70°C. <i>Dil. water.</i>
Methylene iodide.	S.G. 3.32 at 16°C.
Methylene iodide plus iodine.	S.G. 3.548.
Methylene iodide plus iodoform.	S.G. 3.60 — 3.65.
Selenium mono-bromide.	S.G. 3.6 at 15°C. Decomposed by heat; reacts with water.
Sodium mercury iodide.	S.G. 3.46.
Stannic bromide.	S.G. 3.35 at 35°C. M.P. 30°C.
Stannic chloride.	S.G. 2.279 at 0°C., 2.27 at 20°C. M.P. —33°C. <i>Dil. water.</i>
Stannic iodide.	S.G. 4.70 at 15°C. M.P. 143°C.
Stannic iodide plus arsenic tri-bromide.	S.G. 3.73.
Tetrabromethane.	S.G. 2.9.
Thallous acetate nitrate.	S.G. 4.5.
Thallous formate.	S.G. 3.31 at 10°C., 3.40 at 20°C., 4.10 at 50°C.
Thallous formate plus fluoride.	S.G. 4.20 at 20°C., 5.38 at 100°C., 5.40 at 110°C.
Thallous malonate plus formate.	S.G. 4.0 at 10°C., 4.7 at 50°C. (Clerici solution).
Thallous mercurous nitrate.	S.G. 5.3. M.P. 76°C.
Thallous silver nitrate.	S.G. 4.6. M.P. 75°C. Attacks sulphides.
Zinc chloride.	S.G. 2.4 Zinc chloride and lead chloride melt together in all proportions to form mixtures of varying S.G.

Mixtures of any two of the following have been successfully employed in special cases:—

Lead Nitrate.
 Mercuric Nitrate.
 Silver Nitrate.
 Thallous Nitrate.

The above media for heavy mineral separation can conveniently be divided into (1) those which are used as liquids at ordinary temperatures and (2) those which have to be fused or melted before use. In a large number of cases, the compounds are exceedingly poisonous and the greatest care should be taken in their manipulation.

In the case of most of the liquids, since they are expensive, economy is required in their use. Much smaller funnels should be used than with ordinary bromoform separation. Alternatively a small separating funnel fitted with secure stop-cock may be employed; or the simple apparatus described by

F. J. Fraser¹ consisting of a tube wider at one end than the other and bent into a "U" shape. The tube is two-thirds filled with bromoform or other liquid employed and the concentrate introduced into the wider limb. This limb is then corked so that the surface of the bromoform rises to the opening of the narrow limb. The tube is then jerked sideways until the concentrate is uniformly distributed through the wide limb. Care has to be taken to prevent the lighter-than-bromoform

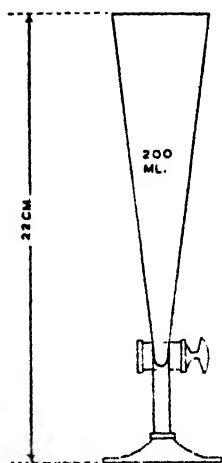


FIG. 7. Spæth Sedimentation Glass.

grains being jerked round the bottom of the tube into the narrow part. After thorough disturbance the tube is held in such a way that the wider limb is vertical and separation is allowed to take place. "The lighter portion of the concentrate having accumulated at the top of the liquid in the wide part of the tube, the process is repeated until the separation of the heavier-than-bromoform grains in the bend of the tube is completed."

The tube is held with the narrow end at left of the operator as he faces it and then slowly turned in an anti-clockwise direction until the narrow limb is vertical with the jet end about $\frac{1}{4}$ in. over a microscope slide.

Choking of the jet by large grains is obviated by pushing in the cork slightly so that a drop falls on the slide. When no more grains can fall down to the jet, the cork is pushed in farther thus expelling two or three more drops on to the slide. The separation is then complete and the minerals ready for drying and mounting.

Another appropriate means is the Spæth sedimentation glass, recommended by A. O. Woodford (Fig. 7).²

Where fused salts are employed separations are most conveniently made in a small test tube, about $\frac{1}{2}$ in. in diameter, the salt and the residue from previous bromoform separation being heated together over a bunsen burner or water bath. In either

¹ *Econ. Geol.*, 23, 1928, p. 99.

² *Econ. Geol.*, 20, 1925, p. 103.

case the heat applied should be the minimum necessary to bring the salt into a clear fluid state, as overheating is fatal. In the fused state, gravitational separation occurs, the lighter particles floating to the surface of the melt, the heavier particles sinking to the bottom. On cooling, solidification ensues, the tube is broken and the "salt core" cleared of any adhering glass fragments. The core is then split in half across the middle by cutting with a knife and thus the part containing the heavier

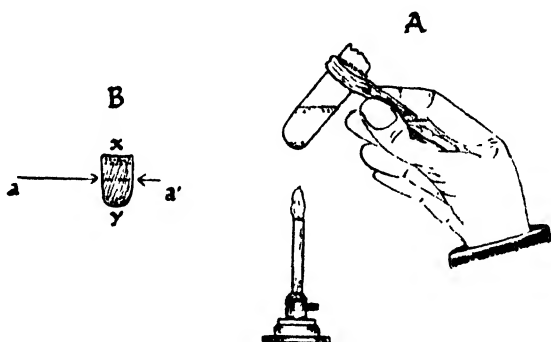


FIG. 8. Diagram to illustrate the use of Fused Salts in Mineral Separation. A, in fluid state with minerals separating out; B, solidified core recovered on cooling; the core is cut along the line a—a', the lighter minerals being held in the part x, the heavier being contained in y.

is separated from that holding the lighter minerals. Each mass is put into a small evaporating dish and the mineral grains ultimately recovered by dissolving the salt in water (unless otherwise stated). *Fig. 8* taken from "Alluvial Prospecting" serves to illustrate the method. With all fused salt separations, manipulation should be as quick as possible to save decomposition and in some cases attack on certain minerals present.

Detrital Mineral Concentration by Hand.—This very tedious, but often necessary, operation is frequently found in the long run to be the most rapid method of obtaining reasonable concentrates of one particular species from a heavy mineral segregation. Minerals possessing some specific property

whereby they can be cleanly selected by physical, mechanical or other means, naturally need no special picking out; but in cases of desired concentrates of such species as epidote, staurolite, pyroxene etc., especially where these minerals are not very prolific in the residue, they will, in ordinary circumstances, have to be isolated by hand. This form of hand-sorting is best carried out with a camel-hair (better still "sable-hair") brush of fine point moistened with cedarwood oil or glycerine and the segregation is made under the microscope, using low power magnification and good transmitted light. As picked out, each grain should be placed in a suitable receptacle; a glazed porcelain tile with twelve or sixteen hollows, as employed for colour-testing in quantitative chemical analysis, answers admirably.

A. D. Howard¹ has described a neat pair of tweezers, constructed of two specially prepared brass pins held in a glass tube, having a device which ensures a tight grip on the mineral grain once secured. This instrument is particularly useful in hand-picking detritals and saves much of the fatigue ordinarily accompanying the brush method.

Elimination of Prolific Minerals from Heavy Residues.

—Core-samples, especially those composed of clay and shale and taken from some depth below the surface, frequently present overwhelming quantities of minerals such as pyrite, pyrrhotite, gypsum etc., which, by masking the less frequently occurring non-opaque species, may render identification and assessment of these a matter of extreme difficulty, so that the residue becomes practically worthless from a petrographic standpoint. Such minerals, once recorded, are best removed; sometimes the initial acid digest does this automatically, but more often than not these minerals find their way into the bromoform residue and have in consequence to be eliminated. It should be noted, however, that in doing so other minerals may be attached and a mount of the original residue should be made as an initial check.

Pyrite is best removed by digesting the heavy residue with weak nitric acid (up to 15 per cent.) or hydrogen peroxide; gentle warming may

¹ *Journ. Sed. Pet.*, 2, 1932, p. 160.

be necessary. It should be borne in mind, however, that certain other minerals present, e.g. apatite, are liable to attack from this treatment.

Pyrrhotite is soluble in hydrochloric acid and can thus be eliminated. Much of this mineral is, however, destroyed by the first acid digest.

Gypsum is a frequent constituent of clay and shale and may be very troublesome in oil-well samples. Because of its low gravity (2.3) it should not appear at all in the bromoform residue, though sometimes, owing to abundant inclusions of iron-ore, it does come down with the heavy suite. It is generally eliminated by the bromoform-benzol solution; it may be attacked by hydrochloric acid; drastic treatment consists in digesting with a strong ammoniacal solution of ammonium sulphate.

Anhydrite has a higher gravity than gypsum (2.9–2.98) and where prolific can be removed with hot, strong hydrochloric acid.

Barite. This mineral is liable to give similar trouble, though it is less frequent in occurrence than pyrite and gypsum in petroliferous rocks; it is not uncommon, however, in sediments associated with saline deposits or in porous sandstones of terrestrial origin in which it acts as a cement; or it may be introduced as a heavy drilling mud. Its elimination can be effected by hot concentrated sulphuric acid in most cases, but the treatment is drastic and may affect other minerals present.

Pyrolusite, for the most part exceedingly local in sediments, may if necessary be removed by digestion with strong hydrochloric acid (warm).

Cloudy Aggregates attached to certain minerals in the form of a film, thus masking the nature of those minerals, may sometimes be removed by nascent carbon dioxide; any violent effervescence may be equally effective, especially with non-ferruginous compounds such as kaolinite, carbonates etc. This treatment is not infallible, however.

Treatment of Argillaceous Rocks.—Clay, marl, extremely fine silt and similar material require substantially different treatment for extraction of accessory minerals from that involved in the case of coarser detritus. Some examples, when dry, are extremely difficult to “break down” under water, though a few drops of ammonia or 10 per cent. solution of sodium carbonate may be effective in this respect. P. G. H. Boswell has described a neat method of making the sample practically red-hot and then plunging it into cold water, to obviate the difficulty; but even this is not always successful and very gentle pulverisation in a mortar may be necessary. Other methods applicable have already been described (p. 62).

An initial concentration may be obtained by repeated washing with water, in much the same way that panning of sands is carried out (p. 65); the resulting material may have to be cleaned with weak acid, but in many instances this proves unnecessary. When dry, a bromoform separation may be tried

and, if the grains are not too small, it may be successful. The author has found, however, that grains of average grade-size <0.01 mm., will not respond readily to such separation, owing to surface tension or other influences and in such cases recourse has to be made to centrifugal methods (p. 67).

An alternative but tedious way is to mount up several slides of the concentrated material and differentiate where possible under the microscope between the essential and accessory minerals. Elutriation (p. 95) may be resorted to, in order to produce a series of graded crops of minerals which may be mounted for examination under the microscope. It is frequently found that concentrations of the "heavy" minerals occur with two or three definite grades and this facilitates their study, but the method is by no means infallible and will most certainly fail with very fine material. Generally speaking, the accessory minerals, as also any detrital quartz present, conform to rather larger grade-sizes than does the clay-substance when pulverised and accordingly it is seldom that one or other of the above methods fails to produce the desired mineral crop.

Shales, mudstones, consolidated marls and similar fine, compact rocks, are treated as crushed samples according to the methods described on p. 80.

Treatment of Calcareous Rocks.—The extraction of heavy mineral residues or of any detrital mineral components from limestones and allied types is not a difficult matter and proceeds either according to the methods described for crushed rocks (p. 80) which is usual, or alternatively acid solubility (p. 192) is employed and the detrital constituents separated with bromoform from the inorganic residuum, preferably with the centrifuge; this last method applies more particularly to soft limestones, oozes and similar materials; most calcareous rocks are hard and compact and need a degree of crushing before they can be treated for mineral concentrates. After acid-treatment of limestones it is often desirable to wash the residue thoroughly to remove clay material as the latter impedes bromoform separation.

Treatment of Carbonaceous Rocks.—The microscopy of coal usually concerns the nature and origin of vegetable structures or coal-substance and, as such, lies outside the scope of

petrology. Consequently few but palaeobotanists are inclined to probe coal-sections deeply; mineralogical evidence is subsidiary to the more fundamental study of the hydrocarbons. Coal may, however, yield heavy mineral assemblages at least as definite and varied as those obtained by panning clays, for instance; not merely ubiquitous pyrite or marcasite, but the more stable detrital constituents may be released by combustion or solution of the organic matter. This phase of investigation was first suggested to the author by W. W. Watts some years ago, since when experiments have been made from time to time on various coals (including lignite) and coal-ash, with interesting though possibly limited results.

The coal substance may be eliminated by burning the coal to ash, washing (by which means much of the light "flaky" matter is disposed of) and drying, then examining microscopically the residue which may be further concentrated by bromoform if desired. The high temperature of combustion is, however, liable to destroy certain minerals. Alternatively the solution method, using aqueous caustic potash, pyridine, phenol, chloroform or sodium hypochlorite has been successfully employed with different types of coal, though some varieties are stubborn (hard bituminous coal and anthracite); gentle pulverisation before solution is necessary.

The average inorganic residue (ash) of coal is seen to consist of quartz (often iron-stained), black particles of metallic ore (some of the latter possibly unburned or undissolved carbon), scaly micaceous matter and stable accessory minerals such as tourmaline, garnet, zircon, rutile; such minerals sometimes resemble those extracted from associated ganisters or grits, or may be quite different, a point of some theoretical significance; other samples have yielded zinc and copper ores.

On searching the literature we find that O. Stutzer¹ records the occurrence of millerite, cinnabar, chalcopyrite, sphalerite, galena, malachite and molybdenite in coal; gold has been found in the coal of Cambria, Wyoming;² silver has been observed in black carbonaceous shale;³ vanadium occurs in coal-ash from

¹ "*Kohle (Allgemeine Kohlengologie)*," Berlin, 1914, p. 19, 193.

² R. W. Stone, *U.S. Geol. Surv., Bull.* 499, 1912, p. 63.

³ T. A. Rickard, *Trans. Amer. Inst. Min. Eng.*, 26, 1896, p. 978.

Scotland,¹ in peat-ash from North Carolina,² in lignite from San Rafael, Mendoza, Argentine³ and in coal from Yauli, Peru;⁴ uranium was detected by A. E. Nordenskiöld in an "anthracite bitumen" from Sweden⁵ and by H. Liebert in the "Kolm" of that country;⁶ radium has been discovered in certain Alabama coals;⁷ germanium and gallium have been found in various British coals.⁸ Although in some of these cases the elements have only been detected during the course of quantitative chemical analysis, the records clearly indicate possibilities of mineralogical interpretation by microscopical examination.

Geologically, the significance of the petrography of coal attaches to the possible indication afforded of its mode of origin; the detrital constituents when localised may suggest direction of transport, hence "drift coal" or "growth-in-situ" may be indicated either by impoverishment or absence of such minerals or by close resemblance of an assemblage to that of intimately associated measures. The potentialities of this phase of petrographic work are obvious, but too much must not be expected of it, especially with bituminous and anthracitic coals. Terrestrial peat, certain lignites and brown coals and especially estuarine coals, form the most encouraging materials to work on. For further data, see p. 409.

Oil-shales, asphalts, asphaltic rocks and various bituminous substances are similarly interesting, the mineral accessories extracted often being sufficiently well individualised to warrant their use as indices of provenance of the material, direction of flow of the bitumen, manner of impregnation and so on. From another standpoint the presence of traces of certain minerals or elements in such substances may attest the action of bacterial or other organisms possessing specially selective or segregative powers, thus throwing light on the complicated mechanism of the genesis of these substances; vanadium minerals in

¹ J. C. H. Mingay, *Rec. Geol. Surv. N.S. Wales*, 7, 1903, p. 219.

² C. Baskerville, *Journ. Amer. Chem. Soc.*, 21, 1899, p. 706.

³ J. J. Kyle, *Chem. News*, 66, 1892, p. 211.

⁴ *Journ. Chem. Soc.*, 70, 1896, pt. ii, p. 252.

⁵ *Compt. Rend.*, 116, 1893, p. 677.

⁶ C. Winkler, *Zeitschr. Kryst. Min.*, 37, 1903, p. 287.

⁷ S. J. Lloyd and J. Cunningham, *Amer. Chem. Journ.*, 50, 1913, p. 47.

⁸ G. Morgan and G. R. Davies, *Chem. and Ind.*, 59, 1937, p. 717.

Trinidad "manjak" and in the "grahamite" of Page, Oklahoma, are cases in point.

Treatment of Bituminous Impregnated Rocks.—Oil-saturated sands, if the hydrocarbon is in a fluid state, can be clarified by repeated digestion of the sample with cold (sometimes warm) benzol, chloroform, ether or carbon disulphide. If, however, impregnation is of a solid asphaltic character, an extraction process must be carried out such as described in Chapter VIII, p. 193. In no circumstances should a sample containing petroleum or asphalt be proceeded with for heavy mineral separation unless such extraction has been carried out, as the presence of the hydrocarbon will discolour and render useless not only bromoform-benzol solution but bromoform itself; recovery of such contaminated bromoform is a very long and uneconomic process; the hydrocarbon also tends to coat individual particles, thus rendering their identification almost impossible. A further difficulty results from the tendency of such impregnated rocks to flux with Canada balsam during the process of making the microscope slides (p. 40).

Treatment of Crushed Rocks for Heavy Mineral Separation.—Compact, consolidated sediments such as sandstones, grits, quartzites, shales, mudstones, ironstones and the like, are normally studied by means of thin sections cut from the samples, as with igneous rocks. But just as the minor accessory minerals frequently escape detection in thin sections of the latter, so it is with sedimentary types and for this reason the supplementary practice of microscopical examination of the crushed material is often, where appropriate, carried out.

The methods, applicable alike to igneous, metamorphic and sedimentary rocks, consist in crushing the sample in a steel mortar until pulverised, avoiding the formation of rock-flour as far as possible. The powder is then panned (p. 65) in water in a 10 in. evaporating basin and in this way the finer light material may be eliminated and the heavier fragments concentrated at the bottom of the basin. As it is often necessary to treat several pounds of rock before an adequate concentrate is obtained, repeated panning is resorted to, using more than one dish at first, but gradually reducing the quantity of material until it can all be concentrated in one receptacle. Panning is,

of course, inadmissible in quantitative work; in such a case, the powder is poured into a beaker of water, stirred, then allowed to settle; the water is decanted and the process repeated until the liquid decanted is clear. Thus obtained, the concentrate or powder is dried in the usual way and then submitted to a bromoform separation to isolate the "heavier" constituents. If the authigenous material is such as to mask the character of the fragments, clarification by means of dilute acid is carried out as previously described.

Recently much intensive research has been conducted on the accessory minerals of granitic and associated rocks, with important results bearing both on their genesis and on their influence as contributors to sedimentary formations. This work follows particularly the lead of A. Brammall and H. F. Harwood in their exhaustive study of the Dartmoor Granite, to which reference is made elsewhere (p. 475). The technique implied follows closely that outlined in the preceding paragraph on crushed rocks and consists in pounding up several lumps of the rock, panning off the light powdery material ("flour") produced, except in quantitative work (see above), thus gradually reducing the bulk until it is of reasonable size for bromoform concentration in the usual way. Thereafter various methods are employed for the isolation of particular mineral species and these minerals are then accorded detailed individual study, both for their own sake and also for the evidence they furnish of geochemical conditions attending the conception and consolidation of the granite. Further reference to this work and to its significance in sedimentary petrological studies will be found on p. 475, also in the Bibliography (p. 618).

CHAPTER IV.

LABORATORY TECHNIQUE (*Continued*).

MECHANICAL ANALYSIS OF SEDIMENTS.

Introduction—Mechanical Analysis—Sieve Analysis—Standard Sieves—Technique—Expression of Results—Fineness Modulus—Elutriation—Andrews Kinetic Elutriator—Air Elutriators—Sedimentation—Pipette Method—Centrifugal Methods—Microscopical Measurement of Particle Size—Particle Size—Shape of Particles.

Introduction.—Before considering methods adopted for their mechanical analysis, a brief description will be given of some of the factors involved in elucidating the mode of formation of sediments.

A river carries in suspension mineral matter which it has abraded from the bottom of its course or eroded from adjacent rocks. On reaching the sea its velocity is checked, with the result that the coarsest particles are immediately deposited. Sand is laid down farther out to sea and finally the clay particles are released as the velocity decreases to zero. In the course of geological time the mouth of the river may become wider, the coast may rise or fall and the areas over which coarse material was initially laid down may later be covered with fine sand, mud etc. A similar result may be produced by alteration in the direction of the currents of the river. It frequently happens, therefore, that a vertical section through a given sedimentary rock sequence reveals a striking assortment of grain-sizes.

Careful examination of a sedimentary deposit often furnishes distinctive evidence of the factors effective in determining its character and in such investigations mechanical analysis is of great importance. A study of the granulometric composition of samples from the same vicinity, coupled with an examination of the shape of individual particles and the

general characteristics of the sediment, may in some instances reveal not only the agency by which it was transported, *e.g.* wind, river water, tidal water, etc., but also its velocity and direction, although in more complex cases such detailed information is not readily obtained. Much valuable knowledge can, however, be deduced from the extent of distribution of grains of a certain size, regularity of bedding, nature of fossils and micro-organisms, presence of ripple and wave marks and other rock structures.

Interesting details of recent methods of correlating horizons in lake sediments are given by G. Lundqvist.¹ These involve fixing the approximate age of the sediments by means of pollen flora, a determination of their composition and structure under the microscope and an examination of the micro-fossils. In carrying out the first determination, a small quantity of sediment is stirred and boiled on a microscope slide with potassium hydroxide, mounted in glycerin and the pollen of distinctive flora picked out under the microscope, the number of each species then being plotted on a frequency diagram. The structure is ascertained by dispersing a known quantity of sediment over a given area on a microscope slide and measuring the relative areas occupied by each constituent. The same slide is used for the examination of micro-fossils.

Among other recent investigators, R. Brinckmann² has examined the structure of fluviatile sediments, T. Wegner³ and W. Wrage⁴ ripple marks, while L. Kolbl⁵ summarises the distinctions between wind and water deposited sediments. The mode of formation in Europe of loess has been discussed by

¹ "Methoden zur Untersuchung der Entwicklungsgeschichte der Seen." *Abderhaldens Handbuch biol., Arbeitsmethoden*, Abt. 9, 1925, Teil 2, 427.

² "Entwicklungsgeschichtliche Binnenseestudien in Südschweden." (Swedish with German résumé), *Sveriges Geol. Undersök.*, Ser. C, No. 330, 1925 (Arsbok 18), Stockholm.

³ "Bodenablagerungen und Entwicklungstypen der Seen." *Die Binnengewässer*, Band 2, 1927, Stuttgart.

⁴ "Über Kreuzschichtung im deutschen Buntsandsteinbecken." *Nachr. Ges. Wissenschaften Göttingen Math.-physik.* Klasse, 1933, p. 1.

⁵ "Unter Gezeiteinwirkung entstandene Wellenfurchen." *Centr. f. Min.*, B, 1932, p. 31.

⁶ "Strombänke als Flutbildungen und eigenartige Oberflächenformen im Schlick. Ein Beitrag zur Kenntnis der Morphologie des Niederelbwassers." *Ann. Hydrographie*, 59, 1931, p. 233.

⁷ "Über die Aufbereitung fluviatiler und äolischer Sedimente. Tschermak's Mineral." *Petrographische Mitt.*, 41, 1931, p. 129.

R. Rungaldier¹ and R. Grahmann² who are agreed that the transportation of river sediments by wind is its most important source. L. S. Berg,³ however, excludes wind action and considers simple weathering to be sufficient explanation. K. Richter⁴ has carried out numerous mechanical analyses of glacial sediments and notes that pebbles of a certain size arrange themselves with their longest axis parallel to the direction and motion of the glacier, thus providing a useful means of determining directions of flow, even when abrasion marks are not visible. Data concerning American glacial deposits are given by G. H. Ashley⁵ and G. A. Thiel.⁶

Mechanical Analysis.—Mechanical analysis is the term usually applied to determination of particle size distribution of grains composing a sediment or mineral aggregate. Where relatively coarse particles are present, as in most types of sand, the operation is carried out by sieving on a set of standard screens or sieves. Owing to the impossibility of manufacturing standard screens with very small apertures which will not soon deteriorate with use and to the rapidity with which such sieves would become clogged, this method is not satisfactory for particles smaller than 0.05 mm. in diameter. If it is desired to classify smaller particles, other means such as elutriation, sedimentation or microscopical measurement must be adopted. In general, it will be found most convenient to grade the coarse fractions by sieve analysis, the fractions down to 10μ ($1\mu = 0.001$ mm.) by elutriation and the -10μ fraction by sedimentation. There are theoretical objections to this procedure in that, for example, the results from sieve analysis and elutriation are not directly comparable; frequently, however, no satisfactory

¹ "Bermerkungen zur Lössfrage, besonders in Ungarn." *Z. Geomorphologie* 8, 1933, p. 1.

² "Der Löss in Europa." *Mitt. Ges. Erdkunde*, Leipzig 51, 1932, p. 1.

³ "The Origin of Loess." *Gerlands Beitrage Geophysik* 35, 1932, p. 130.

⁴ "Die Textur des Geschiebemergels und ihre Bedeutung für die Erforschung des präglazialen Untergrundes." *Z. Geschiebeforschung* 6, 1930, p. 80.

"Die Bewegungsrichtung des Inlandeises, rekonstruiert aus den Kritzen und Langachsen der Geschiebe." *Z. Geschiebeforschung* 8, 1932, p. 62.
 Gefüge und Zusammensetzung des norddeutschen Jungmoränen-Gebietes." *Beih. Z. Geschiebeforschung*, 11, 1933, p. 63.

⁵ "The Scenery of Pennsylvania." *Pennsylvania Topographical and Geologic Survey, Bull. G6* (1933).

⁶ "Report on Sedimentation 1932-34." *Bull. National Research Council* 98, 1935, p. 122.

alternative is available and in any case the error so introduced is unlikely to be serious with approximately equi-dimensional particles.

Geological classification of sedimentary rock particles in this country follows data given by P. G. H. Boswell¹ which did much to remove the then existing confusion regarding interpretation of such phrases as "coarse sand" and "silt"; Boswell's scheme is given below:—

Greater than 2	mm.	Gravel (G)
1 — 2	mm.	Very coarse sand (VCS)
0.5 — 1.0	mm.	Coarse sand (CS)
0.25 — 0.5	mm.	Medium sand (MS)
0.1 — 0.25	mm.	Fine sand (FS)
0.05 — 0.1	mm.	Superfine sand or coarse silt (s)
0.01 — 0.05	mm.	Silt (s)
— 0.01	mm.	Clay or mud (c)

Soil chemists² have adopted a somewhat different nomenclature, reserving the term "clay" for particles below 0.002 mm. in diameter.

2.0 — 0.2	mm.	Coarse sand
0.2 — 0.02	mm.	Fine sand
0.02 — 0.002	mm.	Silt
— 0.002	mm.	Clay

American convention in mechanical analysis follows that employed by C. K. Wentworth and others in which rudaceous constituents are also considered as follows:—

+	256 mm.	Boulder
256 —	64 mm.	Cobble
64 —	4 mm.	Pebble
4 —	2 mm.	Granule
2 —	1 mm.	Very coarse sand grain
1 —	$\frac{1}{2}$ mm.	Coarse sand grain
$\frac{1}{2}$ —	$\frac{1}{4}$ mm.	Medium sand grain
$\frac{1}{4}$ —	$\frac{1}{8}$ mm.	Fine sand grain
$\frac{1}{8}$ —	$\frac{1}{16}$ mm.	Very fine sand grain
$\frac{1}{16}$ —	$\frac{1}{256}$ mm.	Silt particle
—	$\frac{1}{256}$ mm.	Clay particle

Sieve Analysis. — In the past sieve analysis has been regarded with disfavour on the grounds that results are unreliable and difficult to repeat. This state of affairs, partly due

¹ "British Resources of Sands and Rocks Used in Glass Making." (Longmans, Green, London), 1918, p. 13.

² C. E. Marshall, "Mineralogical Methods for the Study of Silts and Clays." *Zeitschr. für Kristallographie (A)*, 90, 1935, p. 8.

to the difficulty of securing suitable screens, was to some extent remedied by the appearance in 1907 of the Institute of Mining and Metallurgy Standard Screens which were quickly adopted by many industries. A feature of the screens was that the size of the apertures was equal to the diameter of the wire employed, the effective sieving area of all screens being therefore 25 per cent. A 200 mesh I.M.M. screen contained 200 apertures and 200 thicknesses of wire to the inch; the aperture was, therefore, $1/400$ th of an inch or 0.0025 in. The advantage of being able to calculate apertures extremely easily was, however, overshadowed by the disadvantages of the small sieving area and lack of any definite relationship between successive sieves.

In 1910, the W. S. Tyler Company, Cleveland, Ohio, U.S.A., put on the market a series of sieves, the apertures of which were in the fixed ratio of the square root of 2, and chose as their basic sieve the 200-mesh sieve, previously standardised by the U.S. Bureau of Standards. This had an aperture of 0.0029 in. and was made from 0.0021 in. wire. Each successive sieve in the Tyler series had apertures exactly half the area of those in the next coarser, or double those in the next finer, sieve. To permit closer sizing to be carried out, intermediate sieves based on an aperture ratio of the 4th root of 2 were added to the series.

In 1919, the Bureau of Standards proposed a new sieve series called the United States Standard Sieve Series and employed the same aperture ratios as the Tyler series, but adopted a sieve of 1.00 mm. aperture as its basic standard. The difficulty that the proposed wire gauges were not standard commercial sizes was overcome by permitting certain tolerances on the wire diameters. This series was adopted by the American Society for Testing Materials in 1926 (A.S.T.M. E11-26) and is now frequently referred to as the A.S.T.M. series. Tyler sieves all conform to A.S.T.M. Specifications and to obviate any difficulty in respect of mesh numbers, carry both the Tyler sieve number and the corresponding U.S. sieve number.

Finally in 1931 the British Standard series of coarse, medium and fine mesh sieves were put forward by the British Standards Institution (B.S. No. 410-1931) and these have since

been extensively employed in this country for all mineral aggregates. The wire gauges specified for the fine and medium sieves are all included in the British Standard Wire Gauge Series and odd mesh counts have been avoided. The screening area of the fine mesh sieves varies from 35-44 per cent., while the apertures of consecutive sieves are substantially in the ratio of the fourth root of two to one. The apertures in the medium and coarse sieves are not based on the fourth root of two, but in every case the increments are simple fractions of an inch, *e.g.* $\frac{1}{32}$, $\frac{1}{16}$, $\frac{1}{8}$, $\frac{3}{16}$, $\frac{1}{4}$, $\frac{3}{8}$ and $\frac{1}{2}$ in. The coarse mesh sieves consist of perforated metal plates of thickness 16 Birmingham Gauge, having square apertures from $\frac{1}{2}$ to 2 in. nominal side (side of square) and of square pitch. The tolerance on all apertures in this series is ± 2 per cent., while the screening area varies from 52-64 per cent.

The common practice of describing fine sieves by "mesh" has been retained, even though this gives no indication of size of aperture unless the wire gauge is known. It is the aperture which is effective in controlling the size of particle passing a given sieve and it is, therefore, more logical to compare sieves on this basis. A lead has already been given by the American Society for Testing Materials in designating sizes by the aperture size expressed in microns and this practice could be adopted with advantage in this country.

Standard Sieves.—A comparison of apertures (mm.) and mesh numbers of the I.M.M., Tyler, U.S. Series and B.S. Series is given below :—

SEDIMENTARY PETROGRAPHY

Sieve Number	Aperture in mm.			
	I.M.M.	Tyler	U.S. Standard (A.S.T.M.)	B.S.
325	—	—	0.044	—
300	—	—	—	0.053
270	—	—	0.053	—
240	—	—	—	0.066
230	—	—	0.062	—
200	0.063	0.074	0.074	0.076
170	—	0.088	0.088	0.089
150	0.084	0.104	—	0.104
140	—	—	0.105	—
120	0.107	—	0.125	0.124
115	—	0.124	—	—
100	0.127	0.147	0.149	0.152
90	0.139	—	—	—
85	—	—	—	0.178
80	0.157	0.175	0.177	—
72	—	—	—	0.211
70	0.180	—	0.210	—
65	—	0.208	—	—
60	0.211	0.246	0.250	0.251
52	—	—	—	0.295
50	0.254	—	0.297	—
48	—	0.295	—	—
45	—	—	0.35	—
44	—	—	—	0.353
42	—	0.351	—	—
40	0.317	—	0.42	—
36	—	—	—	0.422
35	—	0.417	0.50	—
32	—	0.495	—	—
30	0.421	—	0.59	0.500
28	—	0.589	—	—
25	—	—	0.71	0.599
24	—	0.701	—	—
22	—	—	—	0.699
20	0.635	0.833	0.84	—
18	—	—	1.00	0.853
16	0.792	0.991	1.19	1.003
14	—	1.168	1.41	1.204
12	1.056	1.397	1.68	1.405
10	1.270	1.651	2.00	1.676
9	—	1.981	—	—
8	1.574	2.362	2.38	2.057
7	—	2.794	2.83	2.411
6	—	3.327	3.36	2.812
5	2.540	3.962	4.00	3.353
4	—	4.699	4.76	—
3½	—	5.613	—	—
3	—	6.680	—	—
2½	—	7.925	—	—

From this table, it will be seen that the following sieves have nearly identical apertures :—

<i>Tyler.</i>	<i>U.S.Standard. (A.S.T.M.)</i>	<i>B.S.</i>
200	200	200
100	100	100
80	80	85
48	50	52
35	40	36
28	30	25
20	20	18
9	10	8

British Standard sieves to be employed where it is desired to follow P. G. H. Boswell's scheme of classification into gravel, sand, silt and clay are as follows :—

	<i>B.S. Sieve Nos.</i>
1.0 — 2.0 mm.	16 — 8
0.5 — 1.0 mm.	30 — 16
0.25 — 0.5 mm.	60 — 30
0.1 — 0.25 mm.	150 — 60
0.05 — 0.1 mm.	300 — 150

Sieving is not recommended for classification of particles as small as 50μ in diameter; for such particles, elutriation or sedimentation methods should be adopted. If a sieve analysis is employed, however, it is useless to attempt to sieve in the dry state; the fine mineral matter should be washed through with a stream of water and the residue dried and weighed.

Technique.—The bulk sample of sediment is first disintegrated, as far as possible, without fracturing individual pebbles and quartered (p. 27) to an extent depending on the largest pebbles present. If these do not greatly exceed $\frac{3}{4}$ in. in size, a 1 kgm. sample is adequate. The sample is dried, placed on the 8-mesh B.S. sieve and shaken until no more material passes the screen, the purpose of this preliminary separation being to prevent subsequent injury to the delicate mesh of the finer sieves by coarse particles. The coarse material (+8) is sieved first on the $\frac{1}{8}$ in. sieve and then successively on the $\frac{3}{16}$, $\frac{1}{4}$, $\frac{3}{8}$, $\frac{1}{2}$, $\frac{3}{4}$ and 1 in. sieves. If particles larger than 1 in. are present, the analysis is commenced again with a larger sample.

Frequently particles of clay will adhere to pebbles and if these cannot be removed by brushing or rubbing, the $+\frac{1}{2}$ material prior to further screening is washed in a basin. For

precise work, a minimum of water is employed and the latter afterwards evaporated on a steam bath and the residue added to the -8 material. This precaution can, however, often be neglected. The material passing the 8-mesh sieve is weighed and, if clean, a representative portion weighing 100 gm., or alternatively an aliquot portion of the total -8 material, is placed on the finest screen to be employed, say B.S. 200 and again sieved. The residue is weighed and the process repeated on successive sieves, working from the finest to the coarsest.

Sediments are, however, usually dirty and it is advisable to wash the -8 fraction before sieving. This is done by placing the sample in a porcelain basin, covering with water and stirring with a stout glass rod. After allowing to stand for 30 seconds, the supernatant liquid is poured off through the 200 B.S. sieve into another porcelain basin. The treatment is repeated as often as necessary and the wash-water evaporated. The material retained on the 200 sieve is combined with the washed sample, dried, weighed and sieved as above described. Any -200 fraction not completely removed by the process of washing is added to the residue obtained by evaporating the wash-water and reserved for subsequent examination by elutriation or sedimentation.

The action of sieving consists in swirling the particles round the sieve, giving them at the same time a slight vertical motion. The sieve may be tapped in a horizontal direction with the hand, but should not be banged on the bench. Sieving is considered to be complete when not more than 0.05 per cent. by weight of material passes through the sieve after shaking for one minute. The operation is facilitated by employing the mesh without the lid or the pan and sieving over a piece of white or black glazed paper. If the sample contains agglomerates, it is permissible to crush them with the fingers against the side of the sieve, but the pressure must not be directed downwards against the mesh nor must lumps be broken except with the fingers. Particular care is necessary when using the 200-mesh sieve to ensure that lumps are completely broken up and that all fine material is eliminated. The time required may be half an hour or more, although with each of the remaining sieves the operation can usually be completed in a quarter of an hour.

The practice of eliminating the - 200 material first and working from fine to coarse is generally more satisfactory than the older procedure of working from coarse to fine. Where the greatest accuracy is required, sieving should be carried out as described above on each individual sieve, but for certain purposes, sufficiently accurate results are obtained by fitting the sieves together in the form of a nest with the largest sieves at the top and shaking them simultaneously in some form of automatic machine; well-fitting sieves are, however, essential for this purpose if losses are to be avoided. An investigation of the magnitude of the errors involved in this form of sieving has been carried out by C. K. Wentworth.¹

Expression of Results.—A convenient manner of tabulating results of sieve analyses is shown below :—

Initial Sample. Wt. taken 1,000 gm.		Divided on 8 sieve				
		+ 8 — 112 gm.				
		- 8 — 888 gm.				
- 8 fraction Wt. taken 88.8 gm.	Sieve	Wt Retd	Wt. between sieves	Per cent between sieves	Per cent. Cumulative passing.	Per cent Cumulative retained
	200	86.6	2.2	2.2		
			5.1	5.1	2.2	97.8
	100	81.5	2.6	2.6	7.3	92.7
	85	78.9	21.0	21.0	9.9	90.1
	52	57.9	16.6	16.6	30.9	69.1
	36	41.3	10.9	10.9	47.5	52.5
	25	30.4	7.8	7.8	58.4	41.6
	18	22.6	22.6	22.6	66.2	33.8
	8	Nil.			88.8	11.2
+ 8 fraction : Wt. taken 112 gm.	8	112.0	87.0	8.7		
	$\frac{1}{2}$	25.0	25.0	2.5	97.5	2.5
	$\frac{1}{10}$	Nil.			100.0	Nil.

¹ "The Accuracy of Mechanical Analysis." *Amer. Journ. Sci.*, 13, 1927, P. 399.

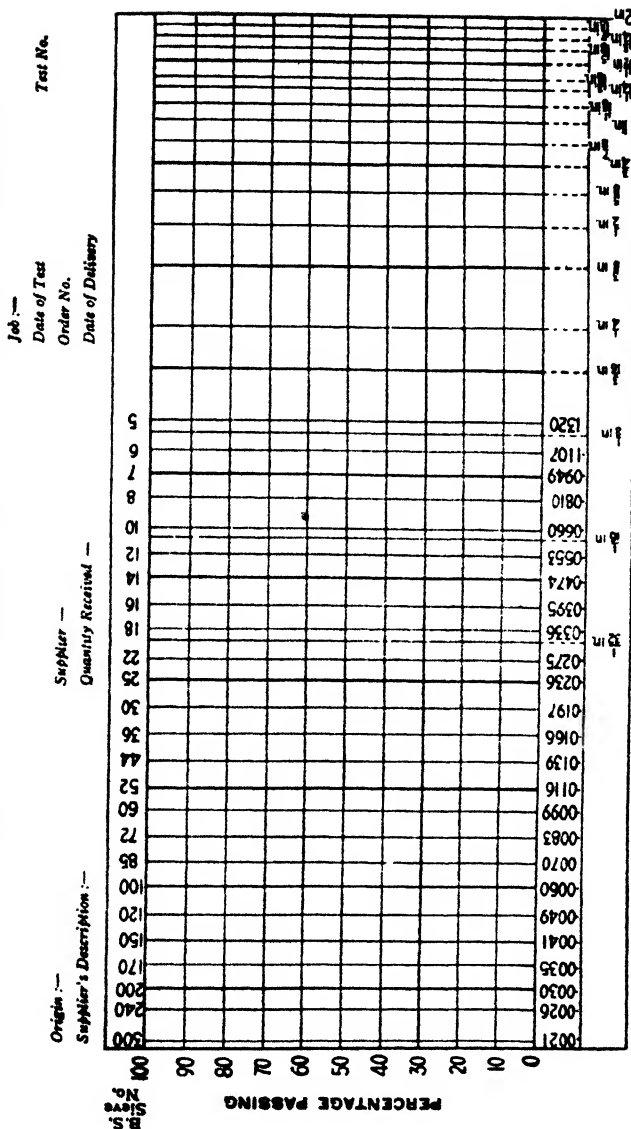
The sign “+” indicates retained and “-” passing. Thus, +200-100 indicates retained on a 200 sieve and passing a 100 sieve; this is usually abbreviated to “200-100.” This figure will be found in the above table in the column headed “Per cent. between sieves” situated between the lines corresponding to the 200 and 100 sieves.

The sieves used in this particular example are not those employed for P. G. H. Boswell's classification (p. 85), but these could have been used if desired. It is, however, a common industrial practice to employ the sieves quoted above for the classification of sands and mineral aggregates and it has been convenient to retain them for work on sediments. Recently a slightly different series of sieves has been standardised,¹ viz. 200, 100, 72, 52, 36, 25, 18, 14, 10, 7, $\frac{1}{8}$, $\frac{3}{16}$, $\frac{1}{4}$, $\frac{3}{8}$, $\frac{1}{2}$, $\frac{3}{4}$, 1, $1\frac{1}{2}$, 2, 3 in. and will no doubt be adopted in the future.

For graphical work, cumulative percentages passing or cumulative percentages retained are plotted against a suitable function of the sieve aperture. With the B.S. fine series of sieves the logarithm of the aperture is a particularly easy value to plot, since the apertures of consecutive sieves are in the ratio of the fourth root of 2 to 1; therefore the logarithms of the apertures are in arithmetical progression and the sieves are equally spaced. This does not hold for B.S. medium and coarse sieves and if the graph has to include them, spacing of the sieves becomes slightly more complicated, unless certain sieves are omitted. The sieves recommended for graphical work are 200, 100, 52, 25, 14, 7, $\frac{3}{16}$, $\frac{3}{8}$, $\frac{3}{4}$, $1\frac{1}{2}$ in. having apertures in the ratio of 1 : 2 : 8 etc. Alternatively any available B.S. sieves may be employed and the results recorded on a form such as that shown in Fig. 9. (Taken from B.S.S. 812—1938.) The advantage of plotting logarithms of apertures instead of actual apertures is that bunching of sieves at one end of the axis is avoided. For further details of graphical methods of expressing mechanical analyses of sediments and

¹ B.S.S. No. 812—1938. Sampling and testing of mineral aggregates, sands and fillers.

GRAPHICAL METHOD OF RECORDING RESULTS OF GRADING OF AGGREGATE.



NOTE : Sieves comply with B.S.S. 410.

FIG. 9. Chart for Recording Results of Grading of Aggregate

(Reproduced by permission from B.S.S. 812-1938. Methods for Sampling and Testing of Mineral Aggregates, Sands and Fillers, copies of which may be obtained from the British Standards Institution, 28, Victoria Street, London, S.W.1, price 3s. 6d.)

probable errors involved in sampling and sieving, the original literature should be consulted.^{1, 2, 3, 4, 5, 6, 7, 8, 9.}

Fineness Modulus.—The fineness modulus of a single particle is a logarithmic function of its diameter. The term was employed by A. Duff Abrams¹⁰ to express the fineness of concrete aggregates and a number of laboratories in this country have since adopted it. For the purpose of determining the modulus of such materials, the aggregate is sieved on A.S.T.M. 100, 50, 30, 16, 8, 4, $\frac{3}{8}$, $\frac{2}{4}$, $1\frac{1}{2}$ in. sieves, or alterna-

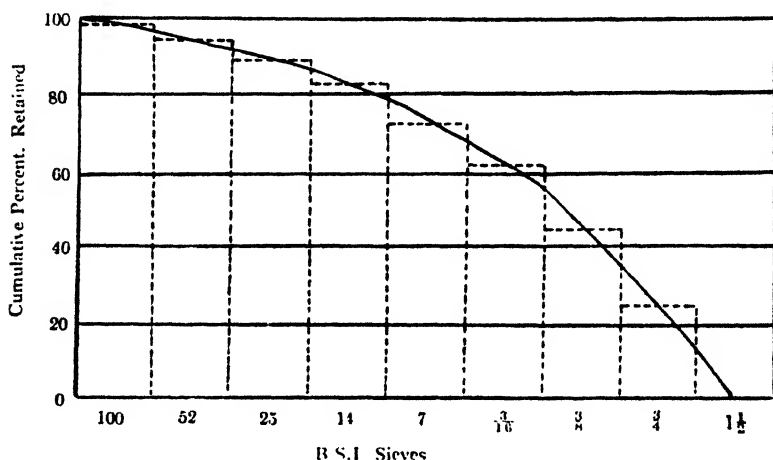


FIG. 10. Fineness Modulus

- ¹ W. C. Krumbein, "Size Frequency Distribution of Sediments." *Journ. Sed. Pet.*, 4, 1934, p. 65.
- ² C. K. Wentworth, "Methods of Mechanical Analysis." *Univ. Iowa, Studies in Natural History*, 11, 1926, p. 46.
- ³ E. W. Galliher, "Cumulative Curves and Histograms." *Amer. Journ. Sci.*, 26, 1933, p. 475.
- ⁴ L. Dryden, "Cumulative Curves and Histograms." *Amer. Journ. Sci.*, 27, 1934, p. 146.
- ⁵ C. K. Wentworth, "A Scale of Grade and Class Terms for Clastic Sediments." *Journ. Geol.*, 30, 1922, p. 377.
- ⁶ D. S. Jennings, M. D. Thomas and W. Gardner, *Soil Sci.*, 14, 1922, p. 485.
- ⁷ W. C. Krumbein, "Probable Error of Sampling Sediments for Mechanical Analysis." *Amer. Journ. Sci.*, 27, 1934, p. 204.
- ⁸ H. A. Baker, "On the Investigation of the Mechanical Constitution of loose Arenaceous Sediments by the Method of Elutriation." etc. *Geol. Mag.*, 57, 1920, p. 321.
- ⁹ D. Macalman, "The Accuracy of Sieving Tests." *Ind. Chem.* 13, 1937, p. 464, 507 and 14, 1938, p. 64, 101, 143, 197, 231, 306, 363, 386, 408.
- ¹⁰ "Structural Materials. Research Laboratory." *Lewis Inst. Chicago, Bull.* 1, 1918.

tively on the B.S. equivalents, *i.e.* the 100, 52, 25, 14, 7, $\frac{3}{16}$, $\frac{3}{8}$, $\frac{1}{2}$, $1\frac{1}{2}$ in. sieves. Both these series of sieves have aperture diameters in the ratio 1:2:4:8:16 etc. The fineness modulus is obtained by adding together the cumulative retained percentages on the nine sieves and dividing by 100. Reference to *Fig. 10* shows that the fineness modulus is simply a number proportional to the area under the grading curve.

The fineness modulus was primarily devised for use with concrete aggregates substantially free from silt and fine particles. It could, however, be extended to include particles belonging to the clay and silt grades and thus meet the more general requirements of geologists. The fineness modulus does not in itself provide a means of expressing the grading of a sediment by a single figure, since two sediments with entirely different ranges of particle size may have exactly the same fineness modulus; but by including suitable upper and lower size limits of the sediment as suffixes to the modulus, this difficulty is to some extent overcome.

H. A. Baker¹ recommends the slightly different method of plotting mechanical analyses of sediments using grade-size as ordinates and cumulative percentage retained as abscissæ. The area under the curve is measured with a planimeter and a factor known as the "equivalent grade" calculated. As this does not define the sediment (any more than fineness modulus) a further term called the "grading factor" is introduced by means of which sediments of the same average particle size are distinguished. The two factors, equivalent grade and grading factor, do not, however, permit the grading curve of the sediment to be reproduced unless certain assumptions regarding its form are made. In fact no entirely satisfactory scheme has yet been put forward which enables sieve analyses to be represented by one, or even two, factors.

Elutriation.—Elutriation is the name given to classification of particles of a substance by means of an upward stream of fluid. In the past it was a common practice to employ elutriation in preference to sieving as a means of classification of particles below 1 mm. in diameter but, with the advent of standard sieves, the necessity for this practice was obviated

¹ *Op. cit*

and sieves can now be satisfactorily employed within the limits previously mentioned. Other methods, such as elutriation, sedimentation and, in certain instances, microscopical measurement must, however, be used to determine the amount of silt and clay grades.

The basic principle underlying all elutriators employed for classification of particles smaller than 50μ is that formulated by Stoke's law. When a spherical particle of diameter D and density D_1 falls under the action of gravity g through a medium of viscosity η and density D_2 , its velocity of fall V is given by :—

$$V = \frac{(D_1 - D_2)gD^2}{18\eta}$$

If instead of being stationary the medium is made to rise with the velocity just greater than V , theoretically the particle will also rise and will ultimately be overflowed from the containing vessel. Elutriation thus consists in placing the sediment in a tubular vessel with a liquid or gaseous medium and weighing the fractions overflowed with increasing upward velocities of the medium. In single vessel elutriators, as the name suggests, all the operations are carried out in one vessel, but in multi-tube types the overflow is conducted through two or more vessels of increasing diameter.

Stoke's law applies only to spherical particles and assumes not only that the sphere is smooth and rigid and that no slipping takes place over its surface, but also that it is placed in a medium of unlimited extent and is unhindered in its fall. Most sediments are not composed of spheres, neither are the surfaces of the particles smooth, while the extent to which their fall is influenced by the presence of other particles or the walls of the containing vessels depends largely on the design of the elutriator. Anomalous results are, therefore, to be expected when one dimension of the particle differs considerably from the other two. For instance, it would be possible so to adjust the overflow velocity that a flat particle could be overflowed and a spherical particle of equal mass and density would sink. For this and other reasons stated below, it is advisable to examine all elutriation fractions microscopically.

Perfect size classification cannot be expected with any elutriator since, although it is theoretically to keep a possible

single particle suspended indefinitely with a certain rising current velocity, or to overflow the particle by slightly increasing the velocity, in actual practice particles are hindered in their motions by the presence of numerous other particles.

Variation in the temperature of the medium will result in a change in its viscosity and density and consequently in the size of particle overflowed. Elutriation is, therefore, carried out at constant temperature or alternatively the velocity is

altered from time to time to compensate for changes in temperature. The viscosity of water at 20°C. changes by approximately 2 per cent. for a 1°C. rise or fall, from which it is evident that change in viscosity is of far greater importance than change in density.

Size classification by means of elutriation cannot be carried out with heterogeneous samples consisting of

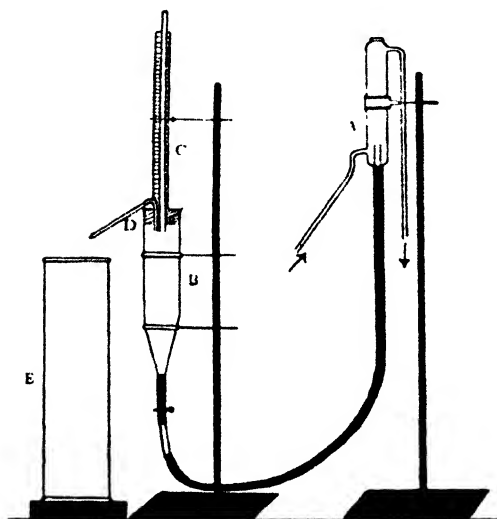


FIG. 11. Single Vessel Elutriator.

A—Constant head apparatus, B—Elutriator, C—Manometer, D—Jet, E—Collecting jar.

particles of different densities as with a given velocity of overflow, the higher the density of the particle, the smaller the diameter overflowed. In a majority of sediments this consideration may be neglected, but where substantial amounts of heavy minerals are present, the sample should be separated before elutriation into crops of different specific gravities and each crop elutriated separately.

Fig. 11 illustrates a common type of single vessel elutriator. The sediment is first dispersed by boiling or shaking with deflocculants, such as 0.05 per cent. solutions of sodium carbonate, ammonia, sodium silicate or soap¹ or by agitating the

¹ P. G. H. Boswell, "The Separation of the Finer Constituents of Sedimentary Rocks." *Trans. Faraday Soc.*, 18, 1922, p. 1.

suspension with live steam.¹ The sample is then washed into the vessel B and the velocity of water passing through the apparatus adjusted by means of the constant head apparatus A and the jet D. The overflow is collected in suitable vessels, allowed to stand, the supernatant liquid poured off and the residue dried and weighed. Coarser grades are overflowed by increasing the velocity of the water. The apparatus must be calibrated before use by measuring the velocity of water at the working temperature required to overflow particles of known size and density.

Full information on single and multi-tube elutriators is given by H. A. Baker,² T. Crook,³ H. Stadler⁴ and A. Holmes.⁵

Andrews Kinetic Elutriator.—Many of the disadvantages of the single vessel type of elutriator have been overcome with the Andrews Kinetic Elutriator⁶ shown in *Fig. 12*. In this apparatus the congestion of particles at the bottom of the vessel and the obstruction of the passage of fine particles by coarser ones is to a large extent avoided, with the result that the elutriator is comparatively rapid and accurate in action.

The following modifications of the standard instrument have been found in the author's laboratories to increase its accuracy and also to enable temperatures to be more easily controlled:—(1) The small constant head tank supplied is replaced by a considerably larger one; (2) the out-flow from the tank is attached to a copper coil immersed in a thermostatically controlled heating bath T and a thermometer (R) enables the temperature of the water to be easily ascertained. Alternatively, the heating coil is interposed between the constant level tank and the main water tap, air bubbles evolved from the water thus being eliminated more easily.

It is advantageous to make all rubber connections as short as possible and to renew them frequently. Before use the apparatus should be thoroughly cleaned from grease with

¹ A. W. Postel, *Journ. Sed. Pet.*, 3, 1933, p. 121.

² *Geol. Mag.*, 57, 1920, p. 321.

³ Appendix to "Sedimentary Rocks," F. H. Hatch and R. H. Rastall (Allen and Unwin, London), 1913, p. 349.

⁴ *Trans. Inst. Min. and Metall.*, 12, 1912, p. 686.

⁵ "Petrographic Methods and Calculations." Part 1 (Murby, London), 1921.

⁶ L. Andrews, "Elutriation as an Aid to Engineering Inspection." *Proc. Inst. Eng. Insp.*, Nov. 25, 1927.

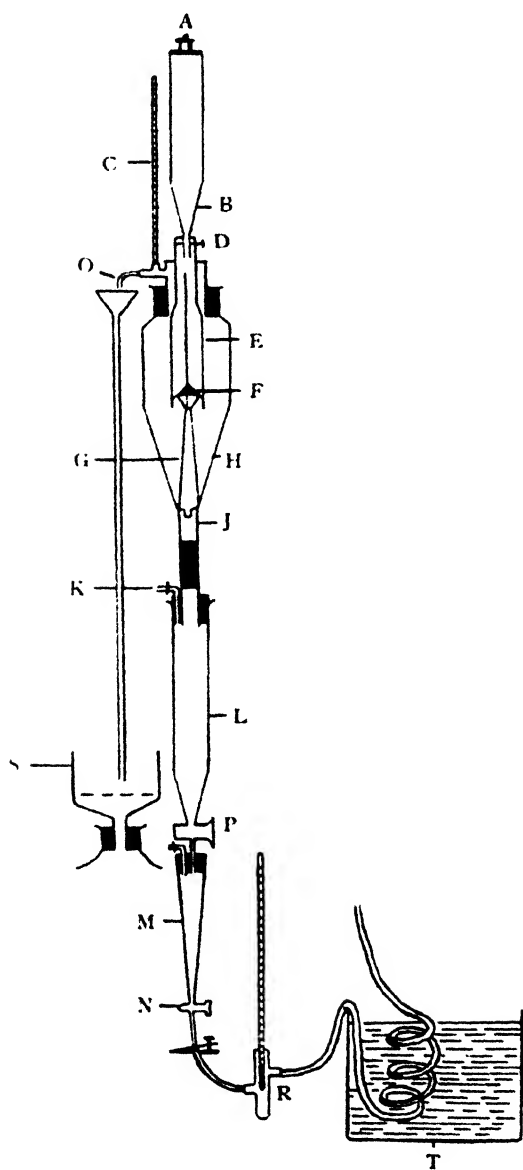


FIG. 12. Andrews Kinetic Elutriator.

chromic acid ; otherwise difficulties may be experienced through particles adhering to the glass. A further precaution is to ensure that the parts of the apparatus are vertical before commencing an experiment. Procedure is as follows :—

The feed-tube B is removed and a small stopper placed in the bottom. The sample (10 gm.) which has previously been dispersed by boiling with water for 5 minutes is then introduced, after which the feed tube is completely filled with water, the top stopper inserted and the air vent closed. The elutriator is allowed to fill with water until it overflows from the jet and the feed-tube is inserted after removing the small stopper. The air vent D is opened and the level of the water allowed to rise and submerge the bottom of the feed tube. The sample then commences to fall into the main classifier in a slow and even stream. When it has been displaced from the feed tube, the air vent A at the top is opened and the water allowed to run from the feed tube into the classifier, after which the vent is reclosed. The sample falls past the annular opening between the tube E and cone F and sinks to the bottom of the classifier H, whence it passes up the hollow central fitting G, strikes the underside of the cone F and passes to the overflow. A piezo-meter tube C indicates rate of flow.

For separation of the -10μ fraction the flow of water issuing from the outlet of the elutriator is adjusted with a measuring cylinder and a stop watch to that shown in the tables accompanying the instrument as necessary to separate particles up to 10μ in diameter (1.5 ml. per second). For this particular separation the entire central fitting can with advantage be omitted, as at this velocity no impact takes place against cone F and the presence of the fitting merely obstructs the opening at J. It is not easy to judge the end-point of separation from the appearance of the liquid in the classifier H and for precise work it is preferable to continue elutriation until not more than 0.2 per cent. by weight of the original sample is overflowed in two hours. The time taken for this separation is dependent on the nature and proportion of fine material present in the sample ; in certain instances it may be as long as forty hours.

The amount of -10μ material may be determined (1) by

passing the overflow direct to a previously dried and weighed filter paper on a Buchner funnel S, filtering under slight suction and subsequently drying to constant weight; (2) by difference, after filtering, drying and weighing the material left in the elutriator; or (3) by difference, without removing the material left in the elutriator but by weighing all subsequent overflows and residues. Method (2) is usually most satisfactory, although it involves re-dispersion of the residue if further fractions are to be separated. It is not advisable to attempt to collect the overflows in large bottles, decant off the water and weigh the residue, as loss invariably occurs when this practice is followed.

The following modification of method (2) has been found satisfactory. The residue in the elutriator after the removal of the -10μ fraction is allowed to settle in vessel L and is then run off into a weighed beaker keeping the volume of liquid as small as possible. The contents of the beaker are allowed to settle for a few minutes; the clean supernatant liquid is then poured off and the remainder evaporated to dryness on the steam bath and the residue weighed. The $+10\mu$ material is then re-dispersed in the same beaker and re-introduced into the elutriator, thus obviating any possibility of absorption of the smaller particles into the pores of the filter paper.

For separation of subsequent fractions, after removal of the -10μ material, the jet is changed for a larger size and the central fitting replaced. The water current is increased to that required to overflow particles approximately 20μ in diameter (4.2 per second) and the overflow again filtered.

When elutriation has proceeded for one hour, the water current is stopped by turning the tap P and the sample is allowed to fall into the classifier L. Particles adhering to the upper classifier H are removed with a rubber policeman.

After half an hour the water current is re-started at the same velocity as before. The coarsest particles are now left behind in classifier L, which has an effective cross-sectional area approximately $\frac{1}{6}$ of the upper, while elutriation proceeds in the upper classifier H as before. When elutriation of the fraction is completed, the elutriator is clipped at J and the tap P quickly turned. If method (2) has been adopted for dealing with the 10μ fraction, there will be no need to recover quantita-

tively the 10—20 μ fraction, providing the remaining fractions are weighed. It should, however, be dried and reserved for microscopical examination. The lower classifier L which contains the particles +63 μ is also detached and its contents washed into a dried and weighed filter paper.

The apparatus is subsequently reassembled, tap K opened and the lower vessel L filled with water. The clip is removed, and the sample again allowed to fall into the lower classifier, after which the overflow is adjusted to 2.75 ml. per second and continued until the upper part of the lower classifier is clear, a process which usually takes less than two hours. The clip J is then replaced, the stop-cock P turned simultaneously and the material in L corresponding approximately to 0.05 μ to 0.06 μ transferred to a filter paper as before. The process of classification in the lower vessel L is repeated with overflows of 1.975 and 1.5 ml. per second, and finally the material remaining in the upper classifier H is also transferred to a filter paper. The graduated vessel M is employed when it is desired to note the volume of the fractions separated in vessel L.

The chart supplied by Messrs. International Combustion, Ltd., with the Andrews instrument, is reproduced below :—

		Upper Vessel			Lower Vessel			
Gauge Reading	Quantity cc./sec.	Velocity mm./sec	Size mm.	Equivalent I. M. Mesh	Velocity mm./sec.	Size mm.	Equivalent I. M. Mesh	
Medium Jet	10.0	4.19	0.56	0.021	600	3.5	0.063	200
	8.5	3.75	0.50	0.02	630			200
	4.5	2.75	0.37	0.016	800	2.3	0.051	250
	2.5	1.975	0.264	0.013	1000	1.65	0.041	300
Small Jet								
4.0	1.50	0.20	0.01	1270	1.25	0.034	375	

In the course of extensive investigation in the author's laboratories with this elutriator, it has been found that, using the velocities given in the above chart at 20°C., and plotting the average particle size (measured microscopically) of the elutriated fractions against the average of the two velocities involved in their removal, the resultant curve is almost coin-

cident with the theoretical curve representing Stokes' law. This applies both for quartz and for substances of higher density, providing the particles are approximately equidimensional, thus confirming that in these circumstances the average particle sizes of elutriated fractions can be calculated from the density of the substance and the basic data for quartz.

The formula employed is :—

$$d_s = D_s \sqrt{\frac{1.65}{D - 1}}$$

where d_s = required average particle size.

D_s = corresponding average particle size for the siliceous filler for the velocities employed.

D = Density of the substance elutriated.

Experiments at the same laboratories on the effect of temperature on elutriation indicated the desirability of controlling temperatures within at least $\pm 0.5^\circ\text{C}.$, from which it follows that use of the elutriator at different periods of the year without any attempt at temperature control leads to serious errors.

Air Elutriators.—Air elutriators have not been used to any great extent in the examination of sediments owing to the difficulty of securing satisfactory dispersion of the particles without the use of an aqueous medium. They can, however, be successfully employed for size classification of certain types of fine mineral powders. The advantages claimed for air elutriation are :—

- (1) Hydration of the particles is avoided and therefore the method can be used for materials such as cement.
- (2) The fractions may be re-elutriated without the necessity arising for re-dispersion.

R. N. Traxler and L. A. C. Baum¹ and P. S. Roller² recommend the use of air elutriators for separating commercial

¹ "Determination of Particle Size Distribution in Mineral Powders by Air Elutriation." *Rock Products*, 37, 1934 (6), p. 44.

² *U.S. Bur. Min., Tech. Paper* 490.

powders such as limestone, pumice and slate into fractions suitable for microscopical measurements. Their procedure is as follows:—

The sample is placed in a glass U-tube, capacity 125 ml., inside diameter 3 cm., one end of which is connected to a classifying chamber and the other to an air inlet nozzle. The latter is connected through a drying chain and flow-meter to a suitable source of compressed air. The velocity of the air is controlled by the size of the inlet nozzle and the diameter of the

classifying chamber. Inter-changeable chambers made of highly polished steel and 20, 10, 5, $2\frac{1}{2}$ and $1\frac{1}{4}$ in. in diameter are used and a mechanical tapping arrangement ensures the return of oversized or undispersed material to the U-tube. A soxhlet extraction thimble is clamped to the top outlet of the classifying chamber to collect the particles removed by the air current.

A current of air is first passed until the thimble assumes a constant weight. The sample is then introduced and the air velocity adjusted to that required for the removal of particles less than 2μ in diameter with the 20 inch classifying chamber. The thimble is removed and weighed at hourly intervals until the increase in weight is less than 10 per cent. of

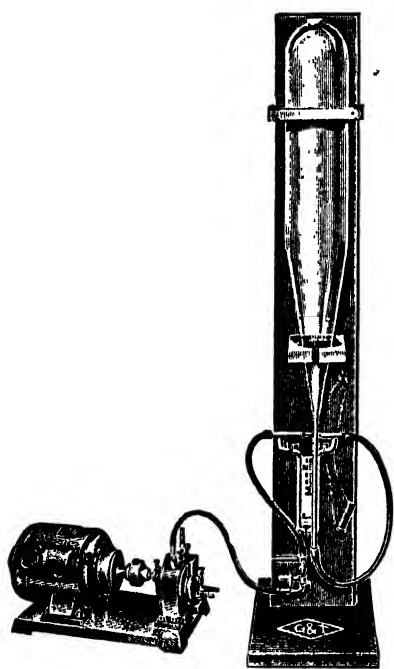


FIG. 13. Mayntz Petersen Flourometer.

the fraction obtained in the first hour. The velocity is then increased to that required to separate the $2-5\mu$ fraction and weighings carried out at 30-minute intervals. To separate particles $5-10\mu$ in diameter, this classifying chamber is replaced by one 10 inches in diameter, the volume of air passing through

the apparatus being kept at its former value. In this case weighings are carried out every 15 minutes. For the separation of the coarser particles, $10\text{-}20\mu$, $20\text{-}30\mu$, $30\text{-}40\mu$, the volume of air is maintained at a constant value, but the diameter of the classifying chamber is successively reduced. Finally, the particle size of all fractions is checked by microscopical measurements.

The Mayntz Petersen "flourometer" has been recommended for standardisation in this country. It consists of a vertical tapering glass tube about 4 ft. long and 4 in. in maximum width, which is connected at the bottom via a 3-way tube to a blower and manometer. The current of air is started and 5 gm. of the sample transferred to the interior of the glass tube without touching the sides. A quarter of an hour later the blower is stopped and the coarse residue weighed. The percentage loss in weight is termed "flour."

The air pressure to be employed is found by trial with the aid of a sample which has been previously examined for flour content on a standard instrument.

Sedimentation.—Elutriation is usually only employed for the separation of particles above about 10μ in diameter and is unsuitable for classification of very fine particles. Sedimentation processes can, however, be employed for measurement of particles as small as 0.2μ in diameter. The procedure is usually indirect since the particles are not actually separated into different sized groups, but their size is deduced by measuring at a fixed point in the suspension, at successive intervals of time, either their weight or hydrostatic pressure. The cost of the apparatus has prohibited general adoption of such methods. The pipette method has not this disadvantage and is very suitable for mechanical analysis of sediments. Little manipulative work is involved except possibly in the dispersion of the sample, which invariably constitutes the principal difficulty in sedimentation analysis. The simple procedure of boiling is not always satisfactory for particles below 10μ in diameter and has been vetoed altogether by some investigators.¹ In general, the methods which have proved efficient combine a mechanical

¹ F. V. Von Hahn, "Dispersoidanalyse." (Steinkopff, Dresden), 1927, p. 272.

process such as soaking,¹ shaking with water,^{2,3} rubber pestling or brushing with a stiff brush,⁴ with a chemical process such as treatment with dilute sodium carbonate, gum arabic or sodium oxalate,³ the exact treatment depending on the nature of the sediment.

For unconsolidated sediments W. C. Krumbein⁵ recommends shaking with dilute sodium carbonate, removing the coarse mineral matter by wet sieving on a 1/16 mm. sieve and diluting the liquid passing the sieve to exactly 1 litre. An original weight of sample is chosen which will give a 2-3 per cent. suspension. The material retained on the sieve is dried and weighed and the difference between this weight and the air-dried weight of the original sample gives the weight of fine material in the suspension. If a moist sample was used initially, a separate moisture content is required. The suspension is examined for the presence of aggregates or flocculates by placing a drop on a microscope slide. If the particles are clustered together or in the form of long chains, dispersion has either not been complete or flocculation has taken place. Preferably some hours should be allowed to elapse after the preparation of the suspension and before making this test. More drastic methods, such as heating to the boiling point, are adopted if dispersion is still incomplete. Primary carbonates should be regarded as an integral part of the sediment and should not be removed by acid treatment. Further information on this subject will be found in papers by W. C. Krumbein⁶ and R. H. Bray, R. E. Grimm and P. F. Kerr,⁷ the former giving a detailed description of dispersion methods adopted for different types of sediments and the latter an exhaustive technique suitable for clays.

¹ W. W. Rubey, "Lithologic Studies of Fine Grained Upper Cretaceous Sedimentary Rocks of the Black Hills Region." *U.S. Geol. Surv., Prof. Paper* 165a, 1930, p. 1.

² A. F. Joseph and O. W. Snow. "The Dispersion and Mechanical Analysis of Heavy Alkaline Soils." *Journ. Agric. Sci.*, 19, 1929, p. 106.

³ L. B. Olmstead, L. T. Alexander and H. E. Middleton. "A Pipette Method of Mechanical Analysis of Soils based on Improved Dispersion Procedure." *U.S. Dept. Agric., Tech. Bull.* 170, 1930.

⁴ D. J. Hissink, "Die Methode der mechanischen Bodenanalyse." *Inst. Mitt. für Bodenkunde*, 11, 1921, p. 1.

⁵ *Journ. Sed. Pet.*, 2, 1932, p. 44.

⁶ "Dispersion of Fine-Grained Sediments for Mechanical Analysis." *Journ. Sed. Pet.*, 3, 1933, p. 121.

⁷ "Application of Clay Mineral Technique to Illinois Clay and Shale." *Bull. Geol. Soc. Amer.*, 46, 1935, p. 1909.

Pipette Method.—The sample is first dispersed by one of the methods given above and one litre of aqueous suspension of known concentration, commonly 2-3 per cent. is prepared. This is transferred to a 1,000 ml. measuring cylinder and well shaken, after which it is allowed to stand for a period of time calculated from Stokes' law, which is sufficient to permit all particles having a diameter greater than 10μ to settle 10 cm. below the surface of the suspension. A pipette is then inserted with its tip exactly at this level and 10 or 20 ml. of liquid withdrawn, evaporated to dryness and weighed. The suspension is then shaken and allowed to stand until particles greater than 5μ have settled 10 cm. and the process repeated. The difference between the weights of the two residues multiplied by the factor (50 or 100) and corrected for the amount of dispersing agent added gives the weight of particles $5\text{--}10\mu$ in diameter. By increasing the time the suspension is allowed to settle and by repeating the process, further subdivisions may be made. The following table shows the time necessary for particles $10\cdot0\text{--}0\cdot1\mu$ in diameter and of average specific gravity 2.65 to settle a distance of 10 cm. in water at a temperature of 20°C .

<i>Diam. of Particle.</i>		<i>Distance.</i>		<i>Time.</i>		
μ	cm.	hr.	min.	sec.		
10	10	—	18	40		
5	10	1	14	41		
2	10	7	47	—		
1	10	31	7	—		
0.5	10	124	30	—		
0.1	10	3112	—	—		

If desired, the settling distance for the finest particles may be reduced to 5 cm., but even so it is rarely practicable to carry the analysis much below 0.5μ on account of the extremely long periods of time involved.

From the description of the method it is apparent that the particles are assumed to be spheres which obey Stokes' law. The results obtained, therefore, give the radius of spheres of the same density as the particles under examination and with the same settling velocities. The validity of the pipette method of sizing naturally depends on the limits of applicability of Stokes' law and various opinions have been expressed on this point. There is, however, reason to believe that with suitable

precautions it can be successfully employed with particles ranging from 50μ to 0.2μ in diameter.^{1, 2}

An interesting application of the photo-electric cell to sedimentation processes is described by D. C. Broome.³ The method depends on measurement of the opacity of a suspension at specified intervals of time but has not as yet been applied to particles smaller than 10μ in diameter.

Centrifugal Methods.—

The chief disadvantage in normal sedimentation processes is the great length of time required to enable the finest particles to settle the required distance; for instance, particles of 1μ in diameter with density 2.65 require 31 hours to sink 10 cm. in water at $20^{\circ}\text{C}.$, while those of 0.5μ require 124 hours as shown above. The centrifuge has been successfully employed by T. Svedberg and J. B. Nichols,⁴ P. D. Trask⁵ and C. E. Marshall⁶ to effect considerable reductions in settling time. A description of the methods utilised by P. D. Trask is given below.

A 6 gm. sample is dis-



FIG. 14.
Pipette Apparatus.
A—Adjusting screw,
B—Slide,
C—Pipette.

¹ F. V. Von Hahn, *op. cit.*, p. 272.

² H. Gessner, "Die Schlämmanalyse," 1931, p. 21.

³ "Testing of Bituminous Substances." (Arnold, London), 1934, p. 86.

⁴ *Journ. Amer. Chem. Soc.*, 45, 1923, p. 2910.

⁵ *Econ. Geol.*, 25, 1930, p. 581.

⁶ "Mineralogical Methods for the Study of Silts and Clays." *Zeitschr. Kristallogr.*, A. 90, 1935, p. 8.

persed by a standard procedure consisting in soaking in distilled water for 24 hours, rubbing with a rubber pestle in water, shaking overnight with 80 ml. of N/24 sodium carbonate and decanting the particles smaller than 50μ in diameter in a special form of tube. The latter are classified by centrifuging 100 ml. aliquot portions of the suspension with the velocities and times necessary for particles of 20, 10, 5, 2, 1 and 0.4μ to settle a specified distance. The volume of sediment in each case is noted, the supernatant liquid decanted and the residue dried and weighed. It was found to be unnecessary to use separate aliquots for each size as the ratio of volume to weight for different sized fractions of a given sediment within the range $5-50\mu$ was constant. Throughout centrifuging operations the temperature of the suspension is kept constant by a forced air draught. The weight of sediment still remaining in suspension after centrifuging to remove the finest particles is determined by comparing the translucency of the suspension with that of standard suspensions containing known weights of similar sized particles. A graph is then plotted showing the percentage of the total weight of sediment accumulating with time and from this curve the size distribution of the particles is obtained. The velocity of settlement of the particles is proportional to the square of the angular velocity of the centrifuge and with a speed of 2,500 revolutions per minute, particles of 0.4μ in diameter settle 10 cm. in 15 minutes.

The centrifuge carries four tubes of the A.S.T.M. Goetz type, having a conical portion graduated in tenths of a ml. with a capacity of about 3 ml. Variations in the velocity of the centrifuge naturally affect results and it has been found most satisfactory to connect the axle of the centrifuge to a constant speed D.C. electric motor. Corrections are then applied for the initial and final periods when acceleration and deceleration are taking place. The formulæ used for this purpose are :—

$$r = \frac{K_2}{W_2 \sqrt{T_r + \frac{T_a'}{3} + T_o' + \frac{T_d'}{3}}} = \frac{K_2}{W_2 \sqrt{T_t'}}$$

$$\text{where } T_r = T_t \left(\frac{W_1}{W_2} \right)^2$$

where r = radius of the particles.

K^2 = a constant.

W_2 = angular velocity during constant period.

T_a' = time during which acceleration is taking place.

T_o' = time during which centrifuging at constant velocity is taking place.

T_d' = time during which deceleration is taking place.

T_t' = time equivalent, assuming a constant velocity of W_2 is maintained throughout.

T_r = time corresponding with the distribution of the particles at beginning of centrifuging.

W_1 = angular velocity during preceding centrifuge interval.

The standard time intervals used by P. D. Trask¹ for acceleration, deceleration and constant velocity at the various speeds of rotation are given in the following table together with the speeds required to separate different sized particles. It should be noted that 20, 10, and 5μ particles are separated from one aliquot, but that separate aliquots are employed for those of 2, 1 and 0.4μ .

STANDARD CONDITIONS FOR CENTRIFUGAL ANALYSIS.

Diam. in μ	R.p.s.	T_a	T_c	T_d	T_t	T_r	T_p	R_1	R_2	R_3
20	6	1.5	17.5	1.5	18.5	—	2.96	7.5	—	—
10	6	1.5	54.5	1.5	74.0	18.5	11.9	30.0	5	—
5	15	4	33	4	47.5	11.9	47.5	120.0	20	—
2	30	8	69	8	74.0	—	296	—	125	5
1	30	8	291	8	296	—	1190	—	—	20
0.4	42	11	937	11	945	—	7400	—	—	125

EXPLANATION.

R.p.s. = revolutions of centrifuge per second = $W/2\pi$.

T_a = acceleration interval in seconds.

T_o = time of running at constant speed W_1 .

T_d = deceleration interval.

T_t = time of centrifuging continuously at constant speed which will produce the same result as was obtained under the conditions of the experiment.

$$T_t = \frac{T_a}{3} + T_o + \frac{T_d}{3}$$

T_r = time representing distribution of particles at beginning of centrifuge interval.

$$T_r = \left(\frac{W_1}{W_2} \right)^2 T_t$$

where W_1 is the angular velocity during the preceding centrifuge interval and W_2 the speed for the interval in question.

¹ *Op. cit.*

T_p = time basis for plotting weight accumulation curve.

$$T_p = T_1 \left(\frac{W}{W_s} \right)^2$$

where $W_1 = 94.25$.

R_1, R_2, R_3 = time ratios used in plotting weight-accumulation curve.

$$R_1 = 2.52 T_p = 6 R_2 = 150 R_3.$$

The data and calculations given by P. D. Trask for a typical example are quoted below¹ :—

DATA AND CALCULATIONS OF SAMPLE 403 FROM MONTEREY BAY,
CALIFORNIA.

Approx. Diam. in μ	Volume Aliquot.	Weight Aliquot.	Weight per cent.	R_1	R_2	R_3
20	.25*	.177	19.7	7.5	1.3	—
10	.44*	.311	34.7	30.0	5	—
5	.69*	.487*	54.3	120.0	20	.8
2	1.04*	.703*	78.2	—	130	5.2
1	1.17*	.782*	87.2	—	—	21.2
0.4	1.22*	.824*	91.8	—	—	133
Fines	—	.008*	.9	Silt-clay vol. 630 cc.		
Sands	.418*†	.066	7.3	Total sample wt. 6.00 gm.		
Total suspended matter	—	.898	100.0	Unaccounted 0.056 gm.		

Sands (50 μ)	...	7 per cent	25 percentile	...	...	13 μ
Silt (5-50 μ)	...	43 "	50 "	...	...	5.0 μ
Clay (1-5 μ)	...	39 "	75 "	...	...	2.1 μ
Colloid (0-1 μ)	...	11 "	Water soluble	...	...	5.9%

* Figures marked with asterisk are observed data, others are calculated.

† Total weight of sands. Figure placed in volume column for convenience.

The above figures are arrived at in the following manner. The weight of sand corresponding to the aliquot of 100 ml. = $\frac{0.418 \times 100}{630} = 0.066$ gm. The total weight of suspended particles in the 100 ml. aliquot portion of the suspension is the sum of the 0.4 μ fraction, the sand and the very fine material not extracted by centrifuging = $0.824 + 0.066 + 0.008 = 0.898$; but the theoretical weight of suspended matter = $\frac{6.00 \times 100}{630} = 0.954$ gm., whence the unaccounted residue which is reported as water soluble material = $0.056 = 5.9$ per cent. The percentages by

¹ *Op. cit.*

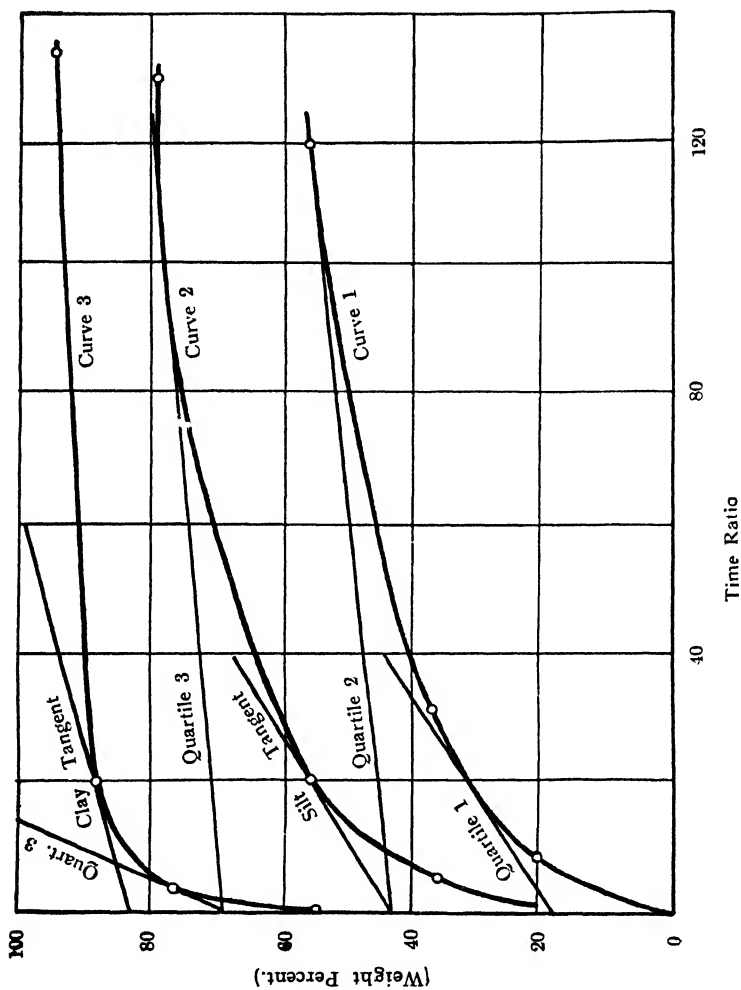


FIG. 15. Weight Accumulation Curves. (After P. D. Trask, *Econ. Geol.* 25, 1930, p. 596.)

weight of the various fractions are calculated on the total suspended matter, *i.e.* 0.898 gm. not 0.954 gm. Thus for the 5 μ fraction, the weight per cent. = $\frac{0.487}{0.898} \times 100 = 54.3$ per cent.

The aliquot weights for the 20 and 10 μ fractions are obtained by calculation from the observed volume of sediment. Three weight accumulation curves are then constructed as in *Fig. 15* by plotting the percentages by weight against the time ratios, R_1 , R_2 , R_3 . The 5-50 μ fraction is found by drawing the tangent on curve (2) at the point corresponding to 20 time units and reading off the value of the intercept on the Y axis, namely 43. Another tangent is drawn on curve (3) at the point 21.2 time units and the intercept found, *e.g.* 82. The difference $82 - 43 = 39$ is the percentage of particles 1-5 μ in diameter. The percentage of colloids is obtained by subtracting the sum of the percentages of constituents greater than 1 μ in diameter from 100.

As an alternative mode of expression, the 25, 50 and 75 percentiles are then found by drawing tangents to the three curves at the points on the Y axis corresponding to 18, 43 and 68 per cent. (*i.e.* allowing for the 7 per cent. of sand present) and converting the time scale to diameters. The percentile is that fraction of the sediment which is composed of particles larger than the dimensions given for the percentile, *e.g.* if the 25 percentile is 15 μ , 25 per cent. by weight of the sediment consists of particles greater than 15 μ in diameter.

P. D. Trask considers that, providing a uniform acceleration and deceleration is achieved and the centrifuge is running for the remainder of the time at constant speed, the centrifuge method introduces no other inaccuracies than the fundamental errors present in all sedimentation processes. In addition to saving time, it is claimed that the method has the further advantages that the water soluble constituents and absorbed water are not included in the weight of the finest portion of the sediment and that the method can be used down to any desired size limit.

C. E. Marshall¹ is of the opinion that ordinary sedimentation processes are inapplicable below 1 μ owing to the disturb-

¹ *Op. cit.*

ing effect of convection currents and recommend the centrifugal method for the separation of particles ranging in size from 2μ to 0.05μ . The fractions separated are $2-1\mu$, $1-0.5\mu$, $0.5-0.2\mu$, $0.2-0.1\mu$, and less than 0.1μ ; a special microscopical technique is employed for the determination of optical characteristics.

Microscopical Measurement of Particle Size.—Microscopical methods are, in general, confined to measurement of particles greater than 1μ in diameter and have a somewhat limited applicability in mechanical analysis of sediments, except in so far as they may be used to check results obtained by other methods. Latterly¹ an attempt has been made to apply microscopical methods to thin sections and to determine particle size of the component grains of indurated sediments, but many factors connected with this type of measurement still await further investigation.

Particle Size.—Some of the ways in which the average particle size of a collection of particles may be recorded are given below:—

- (i) As the arithmetical mean of the diameters of the particles.

$$D_1 = \frac{\sum nd}{\sum n}$$

- (ii) As a diameter which is directly related to the specific surface.

$$D_2 = \frac{\sum nd^3}{\sum nd^2}$$

- (iii) As a diameter related to the volume or weight distribution of the particles.

$$D_3 = \frac{\sum nd^4}{\sum nd^3}$$

- (iv) As the cube root of the arithmetical mean of the volumes of the particles, *i.e.* a diameter which can be used to determine the number of particles per gm.

$$D_4 = \sqrt[3]{\frac{\sum nd^3}{\sum n}}$$

¹ W. C. Krumbein, "Thin Section Mechanical Analysis of Indurated Sediments." *Journ. Geol.* 43, 1935, p. 482.

- (v) As the square root of the arithmetical mean of the surface of the particles, *i.e.* a diameter which can be used to determine the specific surface if the number of particles per gm. is known.

$$D_5 = \sqrt{\frac{\sum nd^2}{\sum n}}$$

- (vi) As the arithmetical mean of the logarithms of the diameters of the particles, *i.e.*

$$\log. D_6 = \frac{\sum n \log. d}{\sum n}$$

Of these methods the second one, namely the surface factor of G. J. Perrott and S. P. Kinney¹ is the most suitable for sediments in that the average diameter so obtained is inversely proportional to the specific surface, *i.e.* the surface area of unit volume of the sediment.

The procedure given below has been found satisfactory for the examination of elutriation fractions containing particles greater than 10μ in diameter and consisting of approximately equi-dimensional particles. If the particles are not equi-dimensional, measurement becomes extremely tedious, as a large number of particles must be examined in all three dimensions. For measurement in two dimensions only, the diameter of an individual particle is taken as the side of a square equal in area to the projected area of the surface visible under the microscope. By the aid of a co-ordinate ruling in the eyepiece of the microscope, this operation can be carried out visually with great rapidity (see p. 160).

The slide for measurement is prepared by placing approximately 1 mg. of the material on a clean microscope slide and dispersing it with a drop of alcohol to cover an area about $\frac{1}{4}$ in. square. When the alcohol has evaporated, an air-mount is made by sealing a cover glass in position with acetone collodion. The slide is then placed under a microscope and the diameter of all the particles in the field determined by noting in turn the number of squares in an eyepiece co-ordinate ruling covered by each particle and taking the square root of this

¹ "The Meaning of Microscopic Measurement of Particle Size." *Journ. Amer. Ceram. Soc.*, 6, 1923, p. 417.

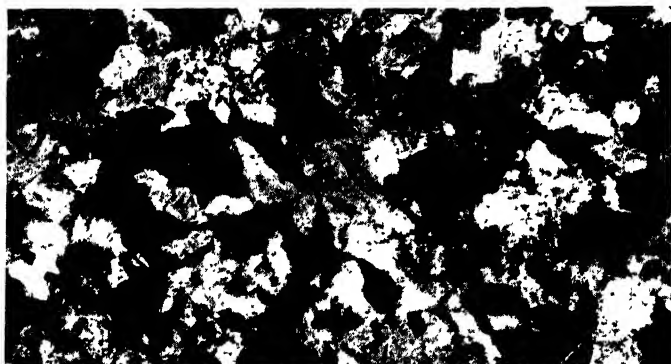
number. The result is usually estimated to the nearest unit or in certain instances to the nearest half unit and a particle recorded by means of a stroke in its appropriate classification (1, 2, 3, 4, 5, 6 etc.). It is quite unnecessary to attempt the exact sizing of each individual particle.

All the particles in one field are measured and the field then changed by moving the screw of the stage micrometer (p. 161), the process being repeated until at least 500 particles have been measured. The fields examined should be distributed as uniformly as possible over the total area of the slide and in the case of small particles (10μ) this necessitates the measurement of considerably more than 500 particles. Greater magnification is necessary if particles below 10μ in diameter are to be examined and can conveniently be obtained by passing a powerful beam of light through the microscope and projecting the image of the particles on to a suitably placed screen.

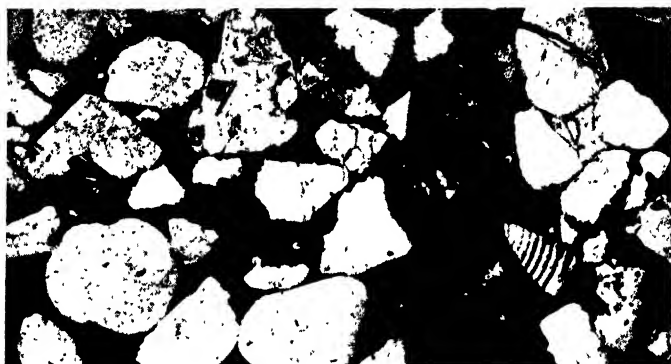
The microscope used in the author's laboratories and described on p. 158 has no petrological accessories, a $1/6$ th inch objective and $\times 6$ ocular with a co-ordinate ruling generally being employed. A convenient size of co-ordinate ruling is that giving squares of apparently 0.01 mm. side when used with a $1/6$ th of an inch object glass, a $\times 6$ eyepiece and a standard length draw-tube. The special auxiliary micrometer (p. 161) fitted to the stage of the microscope permits successive transverse fields to be easily examined and also enables the co-ordinate ruling in the eyepiece to be readily calibrated. This auxiliary micrometer consists essentially of a supplementary stage which is moved in a dove-tailed slide by a screw of 1 mm. pitch. A drum divided into a 100 divisions is attached to one end of the screw and a vernier enables measurements of $1/10$ th of a division, *i.e.* 0.001 mm., to be carried out.

Calibration of the co-ordinate ruling is carried out in the following manner. A small scratch is made on a microscope slide which is placed on the stage and adjusted until the scratch is coincident with one of the lines in the co-ordinate ruling, when the reading on the drum is taken. The stage is then moved until the scratch is coincident with a line 10 or 20 divisions away from the first and another reading of the drum taken. From these two readings the apparent distance between

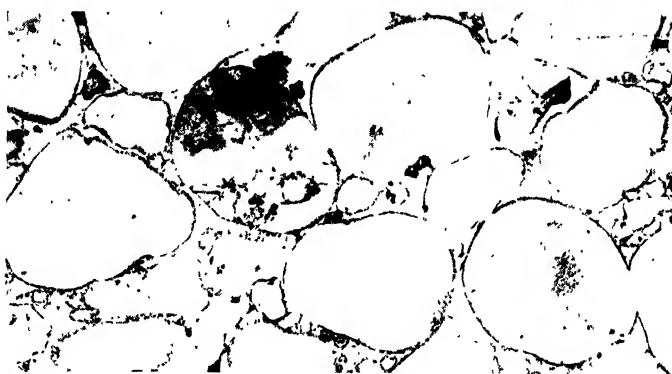
A



B



C



SHAPE OF PARTICLES

- A Angular Pennant Grit (Coal Measures), Bristol [X 38]
 B Subangular Galena-bearing Sandstone (Trias), Alderley Edge, Cheshire [X 25]
 C Rounded Sandston (Permian), Penrith, Cumberland [X 25]

To face page 117

PLATE I.

the rulings can be calculated. Measurements are taken in all parts of the co-ordinate ruling and errors due to backlash (if any) are avoided by moving right across the field with the drum constantly turning in one direction. This combination of a co-ordinate ruling with a travelling stage micrometer is entirely suitable for particle size measurement.

An example of the calculation of the average diameter (surface) is set out below :—

Elutriation fraction 0.03–0.04 mm.

Calibration of co-ordinate ruling : unit of length : $d = 9.6\mu$.

No. of particles n	Size of particles d	nd^2	nd^3	Per cent. by surface
53	1	53	53	0.5
48	2	192	384	2.0
184	3	1656	4968	17.4
301	4	4816	19264	50.6
97	5	2425	12125	25.5
8	6	288	1728	3.0
2	7	98	686	1.0
<hr/> 693		<hr/> 9528	<hr/> 39208	<hr/> 100.0

The average diameter (surface) of the fraction is given by :—

$$\text{Average particle size } d_s = \frac{\sum nd^3}{\sum nd^2} \times 9.6\mu = \frac{39208}{9528} \times 9.6 \\ = 40\mu$$

Assuming the particle size of all the fractions elutriated from a particular sediment can be measured in this way, the average particle size (surface) of the whole sediment may then be calculated from the formula :—

$$\frac{W_1}{d_1} + \frac{W_2}{d_2} + \frac{W_3}{d_3} + \text{etc.} = \frac{100}{D_s}$$

where W_1, W_2, W_3 etc. are the percentage weights of the elutriated fractions and d_1, d_2, d_3 etc. their average particle sizes (surface) and D_s the average particle size of the whole (surface).

Shape of Particles.—Many systems have been proposed for describing the shape of detrital particles which have no sound quantitative foundation and which are, therefore, almost valueless. Workers have for a long period described particles

as rounded, angular, sub-angular etc., and difficulties have frequently occurred in comparing the results of different schools of research, a particle being described as angular by one geologist and sub-angular by another. Various attempts have been made to remove this uncertainty and to formulate a precise method of recording shape (*Pl. 1*).

C. K. Wentworth¹ calculates the mean diameter D of a single grain from the formula:—

$$D = 3 \sqrt[3]{D' D'' D'''}$$

where D' , D'' , D''' are the length, breadth and thickness measured. The roundness ratio is given by:—

$$\frac{r_1}{R} = \frac{2r_1}{D}$$

where r_1 is the radius of curvature of the sharpest edge.

Flatness is given by:—

$$\frac{D' - D''}{D'''}$$

or it may be given by:—

$$\frac{r_2}{R}$$

where r_2 = "radius of curvature in the most convex direction on the flattest developed face or portion of the surface." The radii are measured by a contact method with a gauge similar to that used by opticians to measure curvature of lenses, while the values of r_1/R and r_2/R for each pebble are plotted on double logarithmic chart, the former as ordinate, the latter as abscissa.

W. Mackie² concludes that the rounding of grains is directly proportional to the total friction suffered and inversely proportional to hardness; the friction is a function of the weight, distance travelled and velocity of movement of the grains from which he deduces that for wind transport,

¹ "Shape of Pebbles." *U.S. Geol. Surv., Bull.* 730, 1922, p. 91.

U.S. Geol. Surv. Prof. Paper 131, 1923, p. 83.

"A Laboratory and Field Study of Cobble Abrasion." *Journ. Geol.*, 27, 1919, p. 507.

² *Trans. Edinburgh Geol. Soc.*, 7, 1897, p. 298.

$$R \propto \frac{V \times \text{S.G.} \times D \times V_e}{H}$$

where R =total amount of rounding, V =volume, S.G. =specific gravity, D =distance, V_e =velocity and H =hardness.

For water transport :—

$$r \propto \frac{V \times (\text{S.G.} - 1) \times d \times v_e}{H}$$

where $\text{S.G.} - 1$ =loss of weight due to water displaced.

Thus the ratio of rounding for wind and water, for any mineral of particular grade, is given by :—

$$\frac{R}{r} = \frac{\text{S.G.} \times D \times V_e}{(\text{S.G.} - 1) \times d \times v_e}$$

For a cube it will be noted that :—

$$R \propto \frac{L^3 \times \text{S.G.} \times \frac{d}{4L}}{h} \quad \text{or} \quad R \propto \frac{L^2 \times \text{S.G.} \times d}{4h}$$

where L =the length of one side.

A. C. Tester¹ suggests that an abraded grain should be compared with its estimated original shape and bases his estimate of the degree of abrasion on the ratio of the length of the original edge of the rock to the portion removed by weathering. He employs the terms rounded, sub-rounded, curvilinear, sub-angular and angular to correspond with certain percentages of abrasion. H. Wadell² employs the conception of sphericity and roundness, the former giving the ratio between the surface area of a sphere of the same volume as the particle to the actual surface area of the particle and the latter the ratio between the radius of curvature of a "corner" and the radius of the maximum inscribed circle in the plane of measurement. For a

¹ "The Measurement of the Shapes of Rock Particles." *Journ. Sed. Pet.*, 1, 1931, p. 3.

² "Volume, Shape and Roundness of Rock Particles." *Journ. Geol.*, 40, 1932, p. 443.

"Sphericity and Roundness of Rock Particles." *Journ. Geol.*, 41, 1933, p. 310.

"Volume, Shape and Roundness of Quartz Particles." *Journ. Geol.*, 43, 1935, p. 250.

"Volume, Shape and Shape Position of Rock Fragments in Openwork Gravel." *Geografiska Annaler*, 1936, p. 74.

detailed consideration of this and other proposed methods, reference should be made to the original literature.^{1, 2, 3, 4.}

The measurement of the shape of mineral aggregates has now been standardised by the British Standards Institution⁵ and comprises a determination of the percentage of flaky and elongated material. For this purpose the sample is dried and sieved and each sieve fraction passed through a thickness gauge and a length gauge having openings 0.6 and 1.8 times the mean sieve size respectively. The proportion of flaky material is given by the total weight of aggregate passing the various thickness gauges and is recorded as a percentage of the sample weight. Similarly the proportion of elongated material is given by the total weight of aggregates passing the various length gauges and is also expressed as a percentage of the sample weight.

¹ E. P. Cox, *Journ. Paleont.*, 1, 1927, p. 179.

² C. K. Wentworth, *Journ. Geol.*, 27, 1919, p. 507.

³ "A Field Study of the Shape of River Pebbles." *U.S. Geol. Surv., Bull.* 730C, 1922, p. 93.
Journ. Geol., 27, 1919, p. 514.

⁴ A. C. Tester, *op cit.*

⁵ H. Wadell, *op cit.*

⁵ B.S.S. 812—1938, "Sampling and Testing of Mineral Aggregates, Sands and Fillers."

CHAPTER V.

LABORATORY TECHNIQUE (*Continued*).

FURTHER METHODS OF MINERAL CONCENTRATION.

Magnetic Separation—Electro-magnetic Separation—Electrostatic Separation—Dielectric Separation—Vibratory Methods—Flotation Methods.

IN this chapter are described special methods for effecting heavy mineral concentration other than those concerned with heavy liquids and mechanical analysis. Some of these methods have long been in vogue, *e.g.* electrostatic separation; others are of more recent development. In general these methods are designed to meet particular cases and cannot be said to be universally applicable to all sedimentary rock-minerals; nor do they by any means supplant the simpler high gravity liquid technique in mineral concentration.

Magnetic Separation.—In most cases this follows a preliminary concentration of heavy mineral with bromoform or other medium, though exceptionally, *e.g.* with naturally panned material, a magnetic separation may be advantageous at the outset of examining same.

Before commencing operations, the minerals to be searched with the magnet should be as dry as possible. For strongly magnetic species, such as magnetite, a permanent bar or horse-shoe magnet will be found most effective. The minerals should be spread out uniformly on a flat, white (preferably glossy) surface and the magnet passed systematically just above (not within) the mass, which should constantly be turned over with a spatula to ensure thorough extraction.

For easy release of the magnetite or other mineral thus segregated, it is a good plan to hold over the pole piece(s) a small strip of thin tissue paper, which is easily detachable from the magnet and from which the extracted mineral will automatically drop once clear of the magnetic field.

Horseshoe magnets fitted with adjustable pole pieces (Fig. 16) give better results than ordinary bar or fixed pole horseshoe magnets in that variation of the gap between the points creates a magnetic field of greater or lesser intensity,

whereby less strongly magnetic minerals than magnetite may be segregated. Such magnets are of considerable use, especially in the field when concentrating alluvial minerals. In this connexion J. D. Falconer¹ described a means of achieving a very strong magnetic field (when an electro-magnet is unavailable) consisting of four horseshoe magnets (with adjustable pole pieces) bound together.

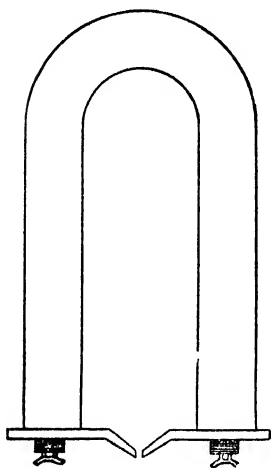


FIG. 16. Horseshoe Magnet with Adjustable Pole Pieces.

For purposes of testing the efficiency of bar and horseshoe magnets (with and without adjustable pole pieces in the latter case) trials should be made with the following minerals purposely mixed to form a concentrate :—

magnetite
ilmenite
almandite
monazite
zircon

See also full list on p. 126.

Electro-magnetic Separation.²—" Where provision for an electro-magnet can be made, this is a far more convenient and flexible apparatus with which to work, since magnetic intensity can be made to vary with the resistance of the current used, with the distance between the pole pieces, or according to the space allowed between the ends of the pole pieces and the con-

¹ *Nature*, 78, 1908, p. 247.

² This, and the succeeding paragraphs on Electrostatic Separation, Dielectric Separation and Vibration Methods, are taken from "Alluvial Prospecting" by C. Raeburn and H. B. Milner (Murby, London), 1927, p. 238.

centrate. In this way a concentrate, whose strongly magnetic minerals have already been abstracted with a bar or horseshoe magnet, may be divided into moderately magnetic, weakly magnetic, and non-magnetic crops; or, of course, the electro-magnet may be used for the entire separation. It will be found that repeated searching of the crops with the magnet is necessary to arrive at cleanly segregated groups, and the achievement of the four distinct grades, strongly magnetic, moderately magnetic, weakly magnetic and non-magnetic, is not as easy as would appear at the outset, largely for the reason

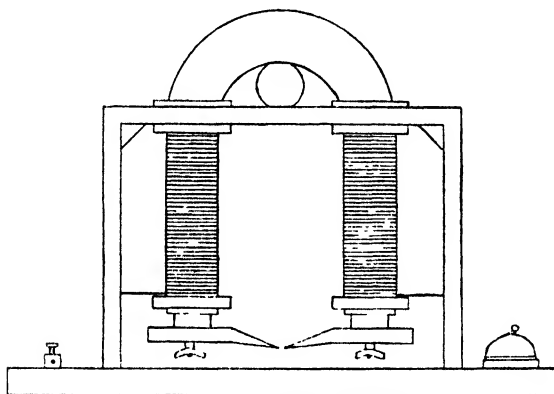


FIG. 17. Electro-Magnet.

that the minerals themselves vary considerably in their magnetic properties, even similar species in the same concentrate.

"Electro-magnets are made to several designs, but the principle of all patterns is much the same. *Fig. 17* shows one satisfactory type employed by the authors.

"The current is supplied either by an accumulator, suitable battery or direct from light or power supply, in which case an adequate resistance must be placed in the circuit. If electric lamps wired in parallel are used for this purpose, the resistance can be altered by decreasing or increasing the number in circuit, resistance (ohms) varying inversely, and current (ampères) directly as the number of lamps employed; the lamps should each be of similar candle-power or watts. Alternatively,

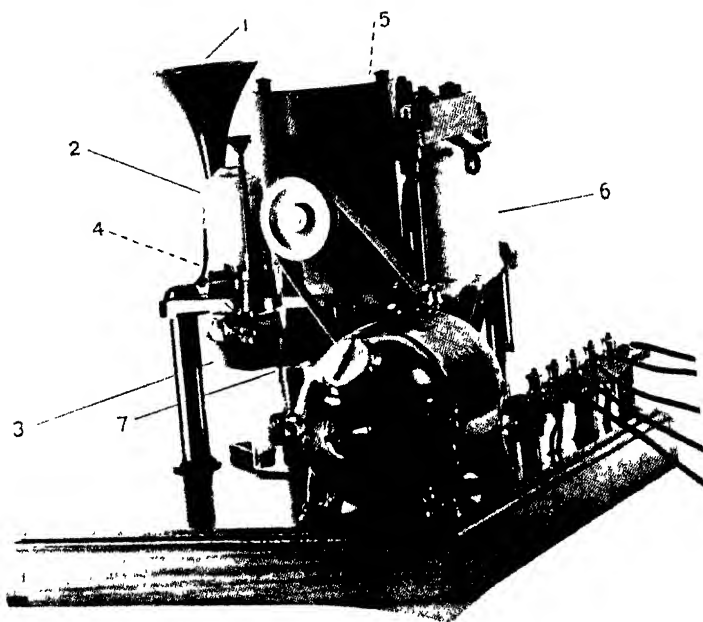
a suitable rheostat may be used for controlling the resistance. The design of electro-magnet chosen will, to a great extent, depend on the nature of the separations which will commonly be made, the power available, and other local circumstances."

Electro-magnetic separation of minerals in the laboratory has been facilitated by A. F. Hallimond,¹ who has designed an instrument capable of dealing with the less magnetic minerals and of giving a clean separation. It has been found that commercial separators cannot easily be adapted to laboratory requirements, since normal practice in design of these is to interpose a conveyor between the pole pieces. Consequently, as soon as the scale of the plant is reduced it becomes impossible to incorporate a sufficiently strong conveyor without at the same time producing a wide gap in the magnetic circuit.

The principle embodied in this new type of laboratory separator is to feed the material directly beneath a double-pole magnet, both poles being above and close to the conveyor. When the magnet is above an opening in the surface of the conveyor, the magnetic material is discharged by interrupting the current. *Pl. 2* shows details of the design of this separator.

Procedure is as follows:—after grading, the mineral powder is placed in the feed hopper (1) which is closed by a valve. Beneath a small table there is a conveyor disc (3) which is rotated clockwise by a small motor. The disc is grooved near the outer edge and the material is carried in this groove. At intervals the groove is cut away, leaving 4 shelves with alternate gaps through which the magnetic material can be discharged. On rotation of the disc, the shelves pass beneath the hopper-mouth. At a given moment contact is made by a mercury tube switch operated from the central spindle (supporting the conveyor disc) and the armature of the feed valve is thus raised by the electro-magnet. A small quantity of material is in this way deposited on each shelf. The shelf then passes below a small single pole magnet (4) which removes any magnetite present, a large magnet (5) for garnet and a final magnet (6) for monazite. After discharge by interruption of

¹ "An Electro-magnetic Separator for Mineral Powders." *Mineral. Mag.*, 22, 1930, p. 377.



HALLIMOND ELECTRO-MAGNETIC SEPARATOR FOR MINERAL POWDERS

<p>1 Feed Hopper</p> <p>2 Magnet Operating Feed Valve.</p> <p>3 Conveyor Disc</p> <p>4 First Separating Magnet (hidden from view)</p>	<p>5 Second Separating Magnet (hidden from view)</p> <p>6 Final Separating Magnet</p> <p>7 Brush</p>
---	--

PLATE 2.

the current of the magnetic fractions through their respective gaps into glass dishes below, the residue is finally passed under a brush which sweeps the bottom of the groove and carries the material into another glass dish. The operation can then be repeated immediately.

To avoid misidentification of mineral grains which, after electro-magnetic separation, may have strayed into the wrong fraction, it is often desirable to be able to determine magnetic properties of individual grains. It may also be desirable to determine magnetic properties of single grains where an electro-magnet is not available. A simple device has been invented by F. Smithson¹ to achieve these ends. A piece of card-board approximately $1\frac{1}{2} \times 1\frac{1}{2}$ in. is folded at one end to give a square $1\frac{1}{2} \times 1\frac{1}{2}$ in. Two darning needles, after being heated to redness and allowed to cool slowly, are pushed through the fold of the card at about $\frac{1}{2}$ in. apart and secured by seccotine so that the points are close together. The needles are placed on a horseshoe magnet and a strong magnetic field thus achieved between the points. To facilitate operations several sets of needles should be prepared with varying distances between the points. The distances between the points should be marked on the card and also the letters "N" and "S," so that they are always placed on corresponding poles of the magnet.

It is advisable to immerse the material to be tested in a liquid medium, *e.g.* benzol or bromoform. As the needle points approach the grains, their behaviour is observed under the microscope. The nature of the magnet used, distance between needle points, magnetic properties of the mineral, size of mineral grains and nature of the liquid medium employed are all factors which will influence the behaviour of the grain under observation.

Whatever means are employed for segregating minerals according to their magnetic properties, for all practical purposes in sedimentary petrology a division into magnetic and non-magnetic crops normally suffices. Where it is a question of isolating a particular species, *e.g.* in sufficient amount for

¹ "A Simple Method of Observing the Magnetic Properties of Mineral Grains." *Mineral. Mag.*, 22, 1930, p. 419.

chemical analysis, then much narrower division is necessary, so that four crops at least are realised, *highly magnetic, moderately magnetic, weakly magnetic, non-magnetic*. With a powerful and sensitive electro-magnet, subdivisions within the second of these crops may occasionally be made in suitable circumstances, *e.g.* separation of garnet and ilmenite, both normally together in the “moderately magnetic” crop.

The following is a list of minerals occurring in sediments which may be expected to reveal magnetic properties to a greater or lesser extent. The student is warned, however, that the same mineral may vary considerably in this respect according to composition and source of origin, *e.g.* almandite garnet which is moderately magnetic in some cases and only weakly so in others.

* * Actinolite	* * * Hornblende
* * * Augite (?)	* * Hypersthene (?)
* * * Biotite	* * * Ilmenite
* * * Cassiterite (rarely)	* * * Magnetite
* * Ceylonite	* * Marcasite
* * Chlorite	* * Monazite
* * Chloritoid	* * Muscovite (?)
* * * Chromite	* * Olivine
* * * Cordierite	* * * Picotite
* * Diopside	* * Pyrolusite
* * Epidote	* * * Pyrrhotite
* * * Garnet (?)	* * * Sphalerite (?)
* * * Glauconite	* * Staurolite
* * * Hematite	* * Tourmaline

* * * denotes strongly magnetic, separable with a bar magnet.

* * denotes moderately magnetic, separable with a horseshoe magnet (adjustable pole pieces).

* denotes weakly magnetic (sometimes separable with a horseshoe magnet, adjustable pole pieces).

(?) denotes liable to great variation in magnetic property.

N.B.—Non-magnetic species excluded.

Electrostatic Separation.¹ — “Minerals which are good conductors of electricity may often be extracted from a concentrate by means of a glass rod in which a charge is induced by rubbing with silk (+), or ebony or sealing-wax rubbed with catskin or rough flannel (−). The application of this well-known principle was developed in connexion with mineral

¹ C. Raeburn and H. B. Milner, *op. cit.*, p. 240.

separation by T. Crook some years ago.¹ His apparatus consists of two copper plates, one supported above the other; the upper one has its under-surface coated with a thin layer of shellac 'which should be continued over the edge of the plate so as to form a narrow strip around the margin of the other face. At or near the edges of the shellac-covered face there should be insulating supports, which may conveniently be made of two narrow strips of glass cemented to the plate and coated with shellac.' This upper plate, with its supports, is placed on a lower naked copper plate, on which the mineral grains are first placed. On charging the upper insulating plate with the aid of an electrophorus—providing the minerals and the whole apparatus are absolutely dry—the good conductors are attracted to the shellac-covered surface of the top plate, from which they are ultimately removed by lifting the plate and brushing the grains off the lower surface. In this way the non-conductors are left behind on the bottom plate; such a concentrate 'can be finally cleaned as far as possible by the sealing-wax method, which offers fuller control.' Electrostatic methods of separation are extremely useful in isolating such minerals as ilmenite, magnetite, wolframite, columbite and tantalite from cassiterite (sometimes a moderate conductor), quartz, zircon, monazite, apatite etc."

The following is a list of sedimentary rock minerals classified according to their relative conductivities:—

* * Actinolite	* * * Ilmenite
* * Anatase	* * Leucoxene
* * Augite	* * Limonite
* * Biotite	* * * Magnetite
* * Brookite	* * * Marcasite
* * Cassiterite	* * * Picotite
* * * Cassiterite (ferriferous)	* * * Pyrite
* * * Chromite	* * Pyrolusite
* * Diopside	* * * Pyrrhotite
* * Glaucophane	* * * Rutile (ferriferous)
* * * Graphite	* * Sphalerite
* * * Hematite	* * Titanite
* * Hornblende	* * Tourmaline
* * Hypersthene	* * * Wolframite

* * * denotes good conductors easily attracted.

* * denotes moderate conductors, attracted with difficulty.

N.B.—Non-conducting species excluded.

¹ "The Electrostatic Separation of Minerals." *Mineral. Mag.*, 15, 1909, p. 260; 16, 1911, p. 109.

Dielectric Separation.¹—"Prof. B. W. Holman has carried out research on the Hatfield process of dielectric separation as a factor in mineral concentration.² To some extent the application of the principles involved is still in an experimental stage, though the following possibilities are now realised:—

(i) The separation of good conductors from bad ones of low dielectric constant, *e.g.* finely disseminated zinc blende from galena, metallic silver from vein-material.

(ii) The separation of earthy minerals of low dielectric constant from one another or from gangue material, *e.g.* oxides of Ni, Co, U, Vd, Ce, Th, and such minerals as gadolinite, phenacite, carnotite, etc.

(iii) The treatment of tin ores, especially when cassiterite is of very fine grade.

(iv) The separation of heavy minerals from a concentrate of a particular species which is a good conductor or which possesses a fairly high dielectric constant, *e.g.* thoria and ceria from tin concentrate.

"It is apparent that under certain conditions the methods are applicable to mineral concentrates, especially if these are of fine grade. Briefly, the method consists in using a grating immersed in a suitable liquid (whose dielectric constant falls between that of the two minerals it is desired to separate); the parallel bars of the grating are alternately connected up to the two ends of an alternating current, 200-250 volts; the mineral possessing the higher dielectric constant is attracted to the bars, that with the lower dielectric constant being repelled. An example is furnished by quartz and cassiterite: the latter has a dielectric constant (50) and is attracted, while quartz (4.5) is repelled if the grating is immersed in aniline (7.3), amyl alcohol (16) or nitro-benzene (36). 'Minerals which differ from one another in dielectric constant by as little as a whole unit can be so separated if their dielectric constants be below 60.' The following table of dielectric constants is quoted from Holman's paper:—

¹ C. Raeburn and H. B. Milner, *op. cit.*, p. 241.

² *Mining Mag.*, 28, 1923, p. 267; *ibid.*, 30, 1924, p. 132, 181; also *Bull. Inst. Min. and Metall.*, 1924, p. 335.

TABLE OF DIELECTRIC CONSTANTS.

Solids.		Liquids.	
Ebonite	2.5	Kerosene	2.0
Sulphur	3.0	Benzene	2.3
Quartz	4.5	Carbon disulphide	2.6
Rock Salt	5.6	Aniline	7.3
Fluorite	6.8	Acetylene tetrachloride...	10.0
Calcite	7.5	Amyl alcohol	16.0
Mica	8.0	Ethyl alcohol	26.8
Blende	40.0	Ethylene dichloride	18.0
Cassiterite	50.0	Methyl alcohol	35.4
Magnetite	over 50.0	Nitrobenzene	36.0
Rutile	over 50.0	Water	70.0

"It should be remembered that these figures vary with the frequency employed, also that, for some of them, different authorities give very different figures.

"For further particulars of this process, reference should be made to the papers cited."

G. A. Berg¹ has suggested a slight modification of the technique of dielectric separation which he claims gives results more comparable with published constants than those normally obtained. He uses ordinary 60-cycle alternating current stepped up to 880 volts. This voltage is secured by an ordinary radio transformer. "A 1-ampere fuse is placed in the primary circuit and a resistance of 2,000 ohms in the secondary circuit. Wires from the secondary circuit lead to needles mounted on an insulated pencil-like handle." The space between the needle points provides the necessary electric field. The separation takes place in a small flat, glass container. The highly magnetic grains are previously removed from the sample with a magnet. Furfural and benzene are mixed in correct proportion to give a liquid medium of the desired dielectric constant and the needle points immersed therein. Those minerals which have a dielectric constant higher than the liquid medium are attracted by the electric field and those with a lower are repelled. Grains attracted can be transferred to a smaller glass dish in the large container. The needle points are then held in the liquid above the smaller container and subsequently drawn out of the liquid. The grains fall thus into the smaller dish. The smaller dish is then withdrawn with forceps and the grains washed with alcohol.

¹ "Notes on the Dielectric Separation of Mineral Grains." *Journ. Sed. Pet.*, 6 1936, p. 23.

During the course of experimentation with various minerals and adopting this procedure, it was noted that time of immersion in the liquid medium had a definite effect on results obtained. This was especially marked in the case of glauconite, but no attempt was apparently made to determine the relation between time of immersion and the effect on dielectric constants of minerals.

Vibratory Methods.¹—"Some years ago a method was developed for separating certain minerals by induced vibrations, more particularly cassiterite, wolframite, columbite, etc., from vein-quartz or gangue (in the crushed state). The principle depends on imparting frequency to a sheet of paper or a thin metal plate on which the minerals have been placed. The paper or plate is held in suspension horizontally at one end by the left hand, and the necessary vibrations set up by regular tapping with a pencil or a hard instrument with the right hand; alternatively, a thin metal plate is clamped at one end and made to vibrate by resonance, using a tuning fork of suitable pitch; the frequency of vibration depends on the thickness of the plate and the point at which it is clamped. The method is not one of universal application, but with certain concentrates (only ascertainable by trial) it works well.

"When employing vibratory methods of concentration, it is found that if a highly glazed paper or well polished copper or brass plate be used, separation is considerably facilitated; also, minerals possessing a large surface-area in proportion to their thickness, *e.g.* mica, lag behind the more irregularly shaped (and often heavier) species; thus the method is useful for getting rid of excessive mica, light particles of foreign matter, dust etc., though it should be pointed out that the principle involved in the latter cases is that of retardation due to friction rather than to the periodicity set up in the supporting medium and imparted to resonant grains."

Flotation Methods.—Water, oil and froth flotation methods of mineral concentration are well known in ore-dressing technique. Similar methods on a laboratory scale have from time to time been tried with mineral concentrates of small particle size, with varying degrees of success.

¹ C. Raeburn and H. B. Milner, *op. cit.*, p. 242.

In the industry, the term "flotation" according to H. L. Sulman¹ now has a limited application to ore-concentration processes by which particles are suspended in an aqueous ore-pulp and subsequently recovered in an air-bubble froth. There are, however, other methods which can be roughly classified into "filming" processes, or those utilising surface-tension effects at a water surface, "oil-buoyancy" methods where oil is employed both as adhesive and buoyant medium for the particles separated, "adhesion" processes dependent on adhesion between oil or grease and the separable particle, "mineral froth" processes where the froth is produced by gases other than air and "plus-pressure" methods based on the principle of generation of air-bubbles upon mineral and oiled particles by pressure differences.

Flotation methods are applicable to nearly all sulphide ores, minerals in which sulphur and graphite occur in practicable amounts, oxidised ores of lead and copper, oxide minerals (*e.g.* cassiterite), gangue minerals etc.

In practice, froth flotation is achieved by agitating an aqueous ore-pulp (usually not less than 4 parts by weight of water to 1 of ore) with the following reagents: a "froth producing" material such as cresol, amyl alcohol or the soluble portion of an oil. This permits the formation of an extensive froth by slight reduction of the surface tension of the water and the mineral particles attach themselves to the froth; a "froth stabilising" material (usually an insoluble oil) which is absorbed at the sulphide mineral surfaces and stabilises the composite froth by increasing the water-mineral contact angle; a "gangue modifying" substance, *e.g.* a mineral acid, alkali etc., which increases the adhesion between gangue particles and water.

The results of flotation are explained by differences in the degree of "wetting" by water or other liquids suffered by various substances. On withdrawal of a solid substance from a liquid, according to the nature of its surface it remains wet to a greater or lesser degree. Some substances appear to repel moisture and on extraction from liquid become more or less dry. Substances capable of complete wetting by a liquid become true

¹ "A Contribution to the Study of Flotation." *Trans. Inst. Min. and Metall.*, 29, 1919, p. 138.

suspensions therein. In the case of crushed ore and water, preferential wetting effects are not sufficiently marked to permit separation of sulphide minerals from gangue. The differences can, however, be intensified by the addition of reagents and specific procedures and successful flotation thereby achieved.

Normally apparatus used for flotation processes is designed to treat fairly large quantities of ore. H. Sulman and F. K. Picard,¹ however, have described a unit which has been designed for laboratory purposes. The scale of apparatus does not in any way affect the principles of flotation provided it is capable of accurate quantification of reagents added to the ore-pulp, addition of given quantities of oil in the form of a dilute emulsion and dissemination of minute air-bubbles through the pulp. These requirements are met in the apparatus described which can handle a minimum quantity of 10 gm. of ore and give results comparable in accuracy with those obtained on large quantities of material in large units.

B. W. Holmann² has carried out extensive investigations of the various methods of concentrating minerals by water, including panning, elutriation and large scale applications of the principles involved. For further particulars of these methods, the reader is referred to the original paper.

¹ "Apparatus for Small-Scale Flotation Tests." *Trans. Inst. Min. and Metall.*, 32, 1923, p. 124.

² "Water Concentration Tests." *Trans. Inst. Min. and Metall.*, 39, 1930, p. 426

CHAPTER VI.

X-RAY, SPECTRUM, FLUORESCENCE AND MICRO-CHEMICAL METHODS OF MINERAL ANALYSIS.

X-Rays—X-Ray Crystal Analysis—X-Ray Spectrum Analysis—Spectrum Analysis — Carbon Arc Cathode Layer Method — Phosphorescence Spectra — Absorption Spectra — Fluorescence (Ultra Violet) — Pyro-electricity—Micro-Chemical Methods.

X-Rays.—Sir William Crookes observed that an electrical discharge, when passed in a glass tube evacuated to 0·01 mm. pressure, produced a phosphorescence on the walls of the tube opposite the cathode. This was found to be due to the impact on the glass of a stream of minute negatively charged particles (cathode rays) travelling at high velocity. These rays are readily deflected by electric or magnetic fields, but can pass through very thin plates of some metals.

In 1895 R. W. Röntgen proved that another type of rays, of much greater penetrating power than cathode rays, known as X-rays, were formed in a Crookes' tube at the phosphorescent spot. X-rays were found to pass easily through wood, aluminium and paper, but to be absorbed by lead and platinum. They have the power of ionising gases, of causing certain minerals to fluoresce and of affecting photographic plates in the same way as a radio-active substance. Unlike cathode rays, they are not deflected by electric or magnetic fields and do not consist of charged particles, but of electro-magnetic waves of the same character as light waves, although of much smaller wave-length. Their wave-length depends on the nature of the substance struck by the cathode rays. In the modern X-ray tube, this is not the glass composing the tube, but a special target or anti-cathode placed in the path of the rays.

All minerals have not the same opacity to X-rays and this fact has enabled the rays to be successfully applied in the

differentiation of precious stones. Some of the results of D. Doelter's¹ work are shown in the following table² :—

BEHAVIOUR TO X-RAYS.

Group 1.	Perfectly transparent.	Amber, diamond.
Group 2.	Strongly transparent.	Corundum and its varieties.
Group 3.	Transparent.	Opal, andalusite, kyanite, chrysoberyl.
Group 4.	Semi-transparent.	Quartz, topaz.
Group 5.	Weakly transparent.	Spinel, grossularite (hessonite).
Group 6.	Translucent.	Tourmaline, apatite, magnetite.
Group 7.	Practically opaque.	Brookite, andradite (melanite), almandine garnet, beryl, epidote, rutile.

X-Ray Crystal Analysis.—X-rays, being of the same character as light rays, are capable of being polarised and diffracted, but for a long time it was not possible to obtain a suitable diffraction grating. The ordinary grating used with visible light consists of a glass plate with a large number of parallel straight lines very close together. Incident light of a particular wave length is diffracted through a constant angle and, if the distance between the lines is known, it is a simple matter to calculate the wave length of the light.

For X-rays, an ordinary diffraction grating would be much too coarse and no suitable device was forthcoming until 1912 when Laue found that on passing a beam of X-rays through a crystal on to a photographic plate a diffraction pattern was obtained. Sir W. H. Bragg and W. L. Bragg followed up this work, proving that a crystal would diffract X-rays in the same way as the diffraction grating does visible light and that the general formula $2d \sin \theta = n\lambda$ holds where: λ =wave length of incident light, $n=1, 2, 3, 4$ etc., θ =angle of diffraction and d =distance between the lines of the grating or in the case of X-rays the distance between the successive planes of atoms in the crystal. Thus, knowing the distance between the planes of atoms, the wave-length of the X-rays may be determined and their spectrum mapped. Alternatively, if the wave-length of the X-rays is known, the method may be used to determine the distance between the planes of atoms in a crystal. If only one

¹ *N.J. Min. Geol.*, etc., 11, 1896, p. 87.

² C. Raeburn and H. B. Milner, "Alluvial Prospecting." (Murby, London), 1927, p. 323.

type of atom is present, as for example in a diamond, the intensity of the diffracted ray depends on the number of atoms in the particular planes examined. Hence, by varying the disposition of the crystal to the incident rays and measuring the intensity of the diffracted rays, knowledge may be gained concerning the spacial arrangement of the atoms, *i.e.* the space lattice. In a metallic salt such as sodium chloride, the planes containing the heavier atoms produce a more intense diffraction than those containing the lighter.

Recently X-ray crystal analysis has been applied to the study of the structure of clays, chlorites, talc and micas and it has been shown that in each case the molecule is built up of atoms linked together in a comparatively simple manner to form two types of layers, *e.g.* the tetrahedral silica layer (Si_2O_5) and the octohedral alumina layer ($\text{Al}_2(\text{OH})_6$). The unit patterns in each layer have very nearly the same dimensions, a fact which makes it possible for distortionless regular stacking to be achieved. L. Pauling¹ considers that kaolinite has probably an unsymmetrical unit cell composed of two layers only, while pyrophyllite has a symmetrical one with a silica layer above and below the alumina. In the case of the brucite layer ($\text{Mg}_3(\text{OH})_6$), the dimensions of the unit cell differ from those of the silica and alumina layers and therefore the most probable structure for talc is the one involving the least distortion, *i.e.* a symmetrical arrangement analogous to pyrophyllite. The base exchange clays, which have been studied by U. Hofmann, K. Endell and D. Wilm² are also given the pyrophyllite structure of two silica layers to one of alumina. This work has been corroborated by C. E. Marshall³ who showed that the chemical analyses of montmorillonite and beidellite were in complete accordance with the proposed type of structure. A most informative and instructive review of the progress made since inception of the idea of a layer-lattice has recently been published by A. Brammall and J. G. C. Leech⁴ and this paper should be consulted by those interested in the subject.

¹ *Proc. Nat. Acad. Sci., U.S.A.*, 16, 1930, p. 123 and 578.

² *Zeitschr. Kristallogr.*, 86, 1933, p. 340.

³ "Layer Lattices and the Base-Exchange Clays." *Zeitschr. Kristallogr. (A)*, 91, 1935, p. 433.

⁴ "The Layer Lattice in relation to Mineral Chemistry." *Sci. Progress*, 31, 1937, p. 641.

The form of X-ray spectrometer (*Fig. 18*) employed by Sir W. H. Bragg and W. L. Bragg for crystal analysis consists of an X-ray tube, a rotating arm on which the crystal is mounted and a tube or ionisation chamber filled with sulphur dioxide gas. A pencil of X-rays, obtained by passing the beam through two narrow slits in pieces of sheet lead, is diffracted from a crystal face into the ionisation chamber. The latter is pivoted on the same vertical axis as the rotating arm

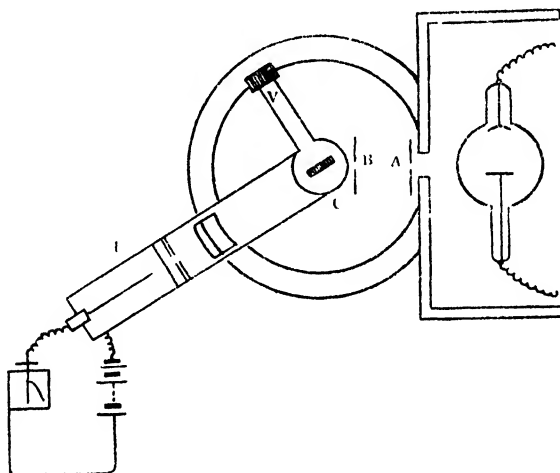


FIG. 18. X-Ray Spectrometer.

A, B, Lead Slits.
C, Crystal.
I, Ionisation Chamber.
V, Rotating Arm moving
over graduated circle.

(After J. R. Partington. "Text-Book of Inorganic Chemistry." (Macmillan, London), 1931, p. 427.)

carrying the crystal and can be moved over a graduated circle. It contains an electrode which is connected to an electroscope. The ionisation chamber is rotated until a diffracted ray enters it and causes the gas to be ionised and discharges the electroscopes. The position of the chamber on the graduated circle is then noted, after which it is again rotated until the next ray enters. The values of θ so obtained are then inserted in the general formula given above.

X-Ray Spectrum Analysis.—The same type of spectrometer is used in X-ray spectrum analysis as in X-ray crystal analysis. When a solid element is bombarded with cathode rays, X-rays of characteristic wave-lengths are evolved, the most important of which are known as the K and L radiations. Moseley in 1914 found that the frequency of the strongest line of the K series was related to atomic number of the element by the formula :—

$$V = \frac{1}{2}K_1(N-1)^2.$$

where V = Frequency of the K Line.
 N = Atomic number of the element.
 K_1 = Rydberg's constant.

From this it follows that once the frequency of the K line has been established, the atomic number of the element may be calculated. As a result of this work, it was possible to determine the number of elements which remained to be discovered having atomic weights between those of hydrogen and uranium. The missing elements at the time were numbers 43, 61, 68, 85 and 87 and of these all except 85 and 87 were subsequently discovered by X-ray spectrum analysis.

The X-ray spectrum examination of minerals is carried out by making the mineral the anti-cathode in an X-ray tube and determining the wave lengths of the emitted radiations by reflection from a crystal face. In general this method is not as sensitive as the carbon arc method of spectrum analysis (p. 141).

Recently B. W. Anderson¹ has described the application of Laue's method of producing diffraction patterns to the discrimination of natural and culture pearls, the obvious advantage of such method being that the destruction of a valuable gem stone is avoided. He found that the difference in density between the mother of pearl nucleus of the culture pearl and the external layers was too small to enable the former to be detected by the ordinary methods of radiography. Applying Laue's method of diffraction patterns, however, natural pearls were found to give a hexagonal spot pattern in all positions, whereas culture pearls give a rectangular pattern unless the nacre layers of the nucleus happen to be normal to the X-ray beam.

¹ *Brit. Journ. Radiology*, 49, 1932, p. 57.

The procedure adopted was therefore to examine the pattern for a rectangular arrangement of spots. If only the hexagonal pattern was observed, another photograph was taken with the axis of the pearl at right angles to its original direction. If the hexagonal pattern again appeared the pearl was of natural origin.

Further details on X-ray methods will be found in the papers listed below.¹

Spectrum Analysis.²—If a solid substance is heated sufficiently, it evolves light, the colour of which depends on the temperature of the solid. If the latter is made high enough, the light will be white in colour and when passed through a prism will give a continuous spectrum due to the different refrangibilities of the component wave-lengths. An incandescent gas or vapour gives a different type of spectrum called a line spectrum which consists of a series of coloured bands or lines characteristic of each element.

Before the spectrum of a mineral can be examined, therefore, it must be converted into a vapour and the means usually adopted are high temperature flames, a spark discharge or the carbon arc. The particular method chosen depends largely on the nature of the mineral and the elements sought. High temperature flames have been successfully employed with alkalis and alkaline earths, but for general qualitative work the carbon arc is more favoured. The spark discharge is suited to rough quantitative work and has the advantage that the intensity of the light is comparatively uniform while, in addition, the spectral lines of many metalloids such as tellurium, carbon, silicon and phosphorus, appear much clearer than with other forms of excitation. A disadvantage of its use is that special devices are necessary for non-conducting materials, such as fusing with sodium or lithium carbonate, dissolving the melt in a suitable reagent and passing the spark through the solution in a specially designed tube.

¹ A. Hadding, "Mineralienanalyse nach röntgen spektroskopische Methode." *Zeit. für anorganische und allgemeine Chemie*, 122, 1922, p. 195.

— "Kvalitativ analys enligt röntgenografisk metod." *Handlingar In. geniors Vetenskaps Akademien, Stockholm*, 11, 1922.

C. E. Eddy, T. H. Laby and A. H. Turner, "Analysis by X-ray Spectroscopy." *Proc. Roy. Soc., London, Ser. A.*, 124, 1929, p. 249.

² A. A. Fitch, "Spectrum Analysis in Mineralogy." (Hilger, London), 1934.

Suitable instruments for the visual examination of spectra are prism spectrometers carrying a graduated drum which enables the wave-length of any particular line to be easily ascertained. Where characteristic lines of an element occur in the ultra violet region of the spectrum, the glass lenses and prisms are replaced by quartz which is more transparent to light of low wave-length than glass and the spectrum photographed.

If it is desired to ascertain by visual means whether a particular metal is present in a mineral, the spectroscope is set up and a small piece of the metal sought, or one of its salts, is introduced into the carbon arc and one or more of the characteristic lines located. The electrodes are then changed for another pair carrying the metal under examination and the eye applied to the spectroscope, while the arc is formed. If the spectrum contains a line in the same position as the characteristic line, it is concluded that the metal is present in the sample. The result may be confirmed by choosing another spectral line and repeating the process.

When photographic means are employed, the spectroscope is fitted with a special device enabling one-third of the slit to be exposed at a time. Through the bottom portion a photograph of the spectrum of the electrodes is taken, through the middle the spectrum of the sample and through the top the spectrum of the metal sought.

Different procedures are used where a full qualitative analysis is required. A common method consists in calculating the wave-lengths of all the spectral lines in the spectrum of the unknown substance. This is accomplished by choosing two reference lines of known wave-length, one on either side of an unknown line and measuring with a micrometer their distance apart and their distance from the unknown line. The wave-length of the latter is then found by simple proportion and the element identified from the tables of wave-lengths of spectral lines. In order to ensure that all the elements present have been detected, another photograph is taken in which the bottom comparison spectrum is that of the elements found. If all the lines in the spectrum of the sample appear in the lower comparison spectrum, no further elements remain to be detected. With experience, the operator learns to

recognise the characteristic lines of certain elements at a glance and the necessity of accurately measuring all wave-lengths is avoided.

An alternative method is to prepare standard composite spectograms by combining the spectrum of the electrodes with that of each metal likely to be present in the sample. Using a micrometer it is then comparatively simple to ascertain whether the lines in the composite spectogram correspond with those in the unknown sample. Theoretically this method can be extended to deal with any number of elements in a given sample, but in practice it is not usually followed with complex mixtures owing to the number of photographs it necessitates. In these circumstances, a better method is to employ a specially prepared powder, known as R.U. powder, which consists of a mixture of 50 elements admixed with zinc, calcium and magnesium oxides. The proportions of the different elements are adjusted so that only the "raies ultimes" and the most prominent lines of the spectra (usually about seven lines per element) appear in the spectrum.

All these methods are qualitative, but they can be made approximately quantitative by employing minerals of known composition as standards. The spectra of these minerals are photographed under carefully standardised conditions and the intensities of the lines compared with the corresponding lines in the spectrum of the unknown sample which has been photographed under exactly identical conditions.

H. Moritz¹ gives further details on the method and procedure to be adopted for qualitative and quantitative investigation. He indicates numerous practical applications of spectrum analysis etc., and provides a useful bibliography on the subject. A. A. Fitch² reaches the conclusion that spectrum analysis is more rapid than chemical analysis though normally not so accurate. Certain spectrographic methods have, however, been evolved which are most valuable for the investigation of alloys and metals. There is also a wide field of application available for this technique in the analysis of mineral concentrates and soils.³

¹ "Chemical Emission Spectrum Analysis." *Min. Mag.*, 51, 1934, p. 21.

² "Spectrum Analysis in Assaying." *Min. Mag.*, 43, 1930, p. 81.

³ R. L. Mitchell, "Spectrographic Analysis of Soils by the Lundegardh Method." *Journ. Soc. Chem. Ind.*, 55, 1936, p. 267T.

Of recent years the discovery of the cathode layer carbon arc method described below has led to great improvements in the accuracy of quantitative work.

Carbon Arc Cathode Layer Method.—The accurate quantitative determination of the minor constituents of rocks, glasses, ores, slags etc., by chemical methods is frequently a matter of considerable difficulty and usually involves long and tedious operations. In the course of a systematic research into the extent of distribution of certain elements in nature, V. M. Goldschmidt¹ in collaboration with R. Mannkopf and his co-workers at Gottigen have devised an extremely sensitive method of spectrum analysis which has proved to be a great advance on the earlier carbon arc and spark methods. The method which is known as the carbon arc cathode layer method is applicable to non-conducting solids and powders and enables most metals to be determined in concentrations as low as 0.0005 per cent. Apart from powdering, no initial preparation of the sample is necessary and only 1-3 mgm. of the material are required for a determination. In fact the use of a larger quantity decreases the sensitivity of the apparatus. In contrast to the earlier carbon arc methods the vaporisation of the material is effected from the cathode and not the anode, as it was found that the line spectra are far more intense immediately in front of the cathode than in the gas column.

The powder to be examined is placed in a small hole in the carbon cathode and the line spectra of the arc examined by means of a spectrograph which has a dispersion high enough to separate the numerous lines. Carbon arcs of an extremely high degree of purity are used. The line spectra are photographed and examined by one of the procedures given below :—

- (1) The intensity of the spectral line is visually compared with the intensity of the same line in a series of carefully prepared standards containing a known proportion of the elements to be determined.
- (2) The comparison is carried out by photometric means, in which case the relative intensity of two lines in the spectrum of the substance to be analysed is compared with the relative intensity of the same two lines in the standard spectra.

¹ L. W. Strock, "Spectrum Analysis with the Carbon Arc Cathode Layer." (Preface by V. M. Goldschmidt). (Hilger, London), 1936.

Considerable care is necessary to achieve a reproducible manipulative technique and to avoid accidental contamination by impurities. A difficulty in the application of this method to the quantitative examination of rocks is that a long and tedious crushing and sampling procedure is involved. The bulk sample of the rock may be several pounds in weight and from this a powdered sample has to be prepared in such a state of division that 1-3 mgm. will be representative of the original rock. An instrument suitable for taking cathode layer arc spectra is shown in *Pl. 3A*, which is a photograph of the Hilger automatic quartz-glass spectrograph fitted with a quartz spherical condenser for focussing the arc sharply on the spectrograph slit.

Phosphorescence Spectra.—This type of spectra was first examined by Sir William Crookes who studied the light emitted when certain rare earths were bombarded with cathode rays in a Crookes' tube. A large number of bands were observed and he erroneously considered that each band corresponded with an element. It was later shown that the pure earths gave no phosphorescence spectra and that the bands observed by him were caused by the presence as impurities of coloured earths. One per cent. of coloured earth gave the most intense spectra and it was found possible to employ this fact to estimate the purity of the rare earth oxides. The method has only a very limited application in the examination of minerals.

Absorption Spectra.—The procedure in this case is to pass white light through a plate of the mineral and to examine the position of the bands in the spectrum of the emergent light with a spectrometer or spectrograph whereby the presence or absence of certain elements may be confirmed. Alternatively, a solution of the mineral may be employed, in which case the position of the bands will depend on concentration, temperature, nature of solvent, the acid radicle present and the thickness of layer. The examination of absorption spectra is not in general suited to the analysis of minerals and information of greater value can be more readily obtained by a study of emission spectra.

Fluorescence (Ultra-Violet).—Ultra violet rays are intermediate in wave length and penetrating power between the

longest X-ray and the shortest visible ray. They are absorbed by many substances and at the same time a visible radiation is emitted giving rise to the phenomenon of luminescence. If luminescence persists when the incident radiation is removed, it is called phosphorescence, whereas if it does not, it is known as fluorescence. Frequently, however, the three terms luminescence, phosphorescence and fluorescence are used synonymously. The colour and intensity of the luminescence may be examined visually or spectroscopically, but the latter method gives information of greater value where quantitative determinations are required. The methods commonly employed for the study of fluorescence have been classified by J. A. Radley and J. Grant¹ as follows :—

QUALITATIVE METHODS :

1. Direct irradiation of a substance or its solution and a comparison of the nature, colour etc., of the fluorescence with that of known samples.
2. Observation of luminescence either by spectroscopic means or with a special form of microscope.
3. Chemical tests involving the production of a fluorescent compound with the aid of suitable reagents or conversely the suppression of fluorescence.
4. Capillary analysis based on the examination of a strip of filter paper soaked in a solution of the substance and dried.

QUANTITATIVE METHODS :

1. Trial and error. Standard mixtures containing the luminescence substance are prepared and matched in ultra-violet light with the sample under examination.
2. Photometry. Under certain conditions the intensity of the luminescence may be measured by photometric means.
3. Capillary analysis. Semi-quantitative work is possible if the intensity of the luminescence of the different zones is measured by photometric means.
4. Fluorescent indicators. These are used to determine the end points in titrations and are especially useful with dark coloured solutions where the end point of the ordinary indicators is not readily discerned.

A great deal of work has been carried out on the application of some of these qualitative methods to the identification of minerals, rocks and gems. F. V. Lutati² found that in most cases it is not possible to identify minerals by their fluorescences, although among the exceptions are calcite, celestite,

¹ "Fluorescence Analysis in Ultra-Violet Light." (Chapman and Hall, London), 1935.

² *Ind. Chimica*, 5, 1930, p. 1222.

fluorite, ruby and zircon. G. F. Kunz and C. Baskerville¹ showed that witherite, strontianite, baryto-calcite, wollastonite and some specimens of glauberite possess very strong fluorescences, while H. Haberlandt² indicated that many of the rare earths exhibited the property of producing an alteration in the fluorescence of the fluorites, although they are not in themselves fluorescent. The same author discovered that some German fluorites had a distinctive red fluorescence which was especially marked after heating or bombardment with β or γ rays, but that others were unaffected by the treatment. The red fluorescence obtained after irradiating with β or γ rays was very similar to that of certain natural fluorites found in radioactive regions and it was concluded that the source of the colour was the same in each case.

The fluorescence of willemite has been studied by L. J. Spencer.³ C. Parache⁴ and others and they reached the conclusion that the natural colour of the mineral could not be correlated with the fluorescence, since some colourless varieties had a violet fluorescence, while the coloured were totally inactive. The variable nature of the fluorescence was attributed to the presence of certain mineral constituents of a strongly fluorescent nature.

Slags which show no tendency to disintegrate on storage and are thus suitable for road making are stated by A. Guttmann⁵ to show a dark violet fluorescence when the freshly broken surfaces are examined, while after weathering yellowish white spots appear. Unsuitable slags give abundant patches of a red-brownish colour possibly due to the presence of particles of γ dicalcium silicate.

H. Michel⁶ and G. Riedl⁷ studying gem stones found it an advantage to employ a colour filter to eliminate the natural colour of the mineral. Diamonds from different localities were found to vary widely in the nature of their fluorescence, some giving no fluorescence at all. Colourless topaz, beryl, quartz

¹ *Chem. News*, 89, 1904, p. 1. *Elektrochem. Met. Ind.*, 1906, p. 435.

² *Sitzber. Akad. Wiss. Wien. Math. Nat.*, 141, 1932, p. 441; 142, 1933, p. 29. *Nature*, 133, 1934, p. 99.

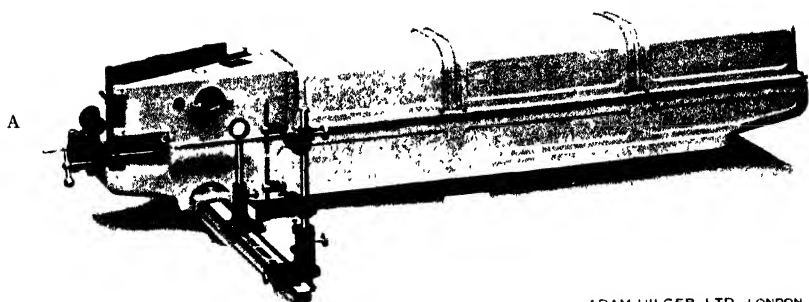
³ *Amer. Mineral.*, 14, 1928, p. 33; *Mineral. Mag.*, 21, 1927, p. 388.

⁴ *Amer. Mineral.*, 13, 1927, p. 330.

⁵ *Stahl und Eisen*, 42, 1926, p. 46.

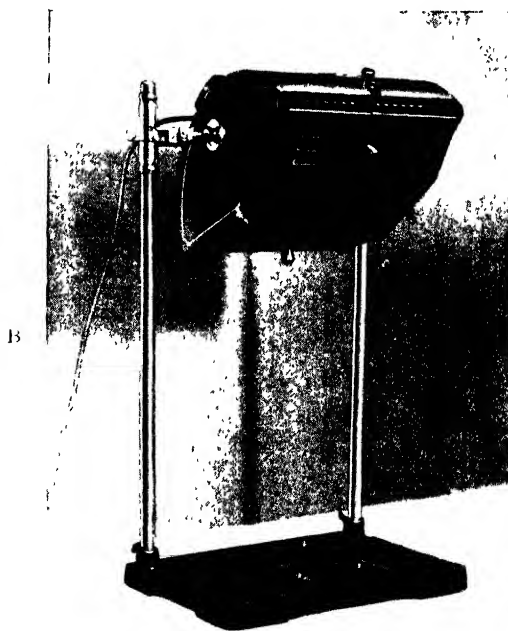
⁶ *Deut. Goldschmiede-Ztg.*, 16, 1926.

⁷ *Gold und Silberschmiede*, 6, Nos. 1-8.



ADAM HILGER LTD LONDON

A. Hilger Automatic Quartz Glass Spectrograph.



B. Hanovia-Muir Analytic Lamp for Ultra-Violet Fluorescence.

and zircon, together with red tourmaline, zircon and garnet were also inactive. Yellow sapphires were distinguished by a pronounced, and yellow topaz by a weak, orange-yellow fluorescence; the other yellow gem stones did not fluoresce. Artificial and natural blue sapphires could be differentiated and Siamese rubies distinguished from Burmese and synthetic varieties. Natural and culture pearls had very similar fluorescences, but differed as regards transparency to the ultra-violet rays. This latter property was demonstrated by placing the pearls on a photographic plate and illuminating with ultra violet light when an area of uniform intensity was produced in the culture pearls and a mottled effect in the natural pearls. Further details of the application of fluorescence methods to the study of minerals, together with a valuable list of original workers, will be found in J. A. Radley and J. Grant's text book, to which reference has already been made.

Ultra-violet fluorescence has been applied for some years at the author's laboratories to the detection and differentiation of bitumens. The mercury vapour lamp used for this purpose is illustrated in *Pl. 3B*. The general procedure adopted is to examine the fluorescence of an 0.5 per cent. solution, weight/volume, of the bitumen in carbon disulphide and compare it with a series of standards of equal concentration. Residual bitumens give bright greenish yellow fluorescences quite distinct from the dull greenish browns of oxidised bitumens, while asphaltic limestones give much yellower fluorescences than the residual bitumens. Trinidad Lake asphalt, Cuban asphalt and Gilsonite also have distinctive fluorescences. The differences in the fluorescences of bitumens are most apparent when the meniscus of the solution is studied and by this means comparatively small variations may be detected. The visual method is, however, difficult to apply to examination of mixtures, although possibly a spectroscopic or photographic technique would be more successful. An 0.5 per cent. solution gives the best results as distinctions become less marked with any increase or decrease in concentration. With substances containing mineral matter, the soluble bitumen content is first determined and a solution prepared of requisite concentration. It is unnecessary to filter if the solution is

allowed to stand before examining the fluorescence, as the mineral matter has no effect on the colour of the meniscus. Unfortunately standard solutions of different types of bitumen cannot be preserved without alteration in the fluorescence even when sealed in glass tubes and kept in the dark. The change in the colour of the fluorescence is most marked in the first few days although thereafter little further change is apparent.

An alternative method which is employed on some occasions is to allow a drop of 0.5 per cent. bitumen solution free from mineral matter to evaporate on a filter paper under the ultra violet lamp, when the yellowish fluorescence initially seen gives place to a characteristic yellowish white rim surrounding a brownish spot.

Pyro-Electricity.—When a crystal of tourmaline is heated, it is found that one end develops a positive static charge of electricity and the other a negative, while on cooling the position of the charges is reversed. A. A. E. E. Kundt employed an extremely ingenious method of observing this phenomenon based on the fact that when a mixture of red lead and sulphur is blown through a muslin sieve, the friction causes the sulphur particles to become negatively electrified and the red lead particles positively electrified. Consequently, if the crystal of tourmaline is placed near the muslin, the sulphur particles travel to the positively electrified parts and the red lead to the negatively electrified parts. Crystals which behave in this manner are said to exhibit pyro-electricity. It was found that the "sharper" end of the tourmaline crystal always assumed a negative charge with rise in temperature and a positive with decrease in temperature. The names "analogous" and "antilogous" were coined to distinguish the two ends of crystals which show pyro-electric properties, the former being that end where addition of heat gives a positive charge and the latter where the converse takes place. All crystals possessing pyro-electric properties have also a polar axis of symmetry, *i.e.* the two ends of the crystal where a principal axis of symmetry emerges have different geometric configurations and advantage is taken of this fact to check goniometrical measurements. A crystal that possesses only one unsymmetrical axis will exhibit pyro-electricity only along that axis, while if the crystal is perfectly symmetrical pyro-electricity will not be developed at

all. The phenomenon of pyro-electricity therefore provides the crystallographer with an extremely easy means of ascertaining the geometrical symmetry of a crystal.

A simple method of detecting pyro-electricity has been described by A. P. G. Martin¹ and is claimed to be extremely sensitive. It has the advantage that the test is carried out at low temperatures whereby the insulating properties of the crystal are increased and, further, the crystal is not destroyed in the course of the examination. The apparatus comprises a Dewar flask containing liquid air in which the crystal is maintained at a constant temperature. A narrow strip of silvering is removed from the flask to enable the contents to be viewed. A metal plate supported on a pivoted glass rod is immersed in the flask and is fitted with a long handle to enable it to be moved small distances with accuracy. The crystal to be tested is suspended opposite the plate by means of a glass fibre to which it is attached by a loop of cotton or Kodak mounting paste. A cork carrying a bent glass rod is attached at the other end of the glass fibre so that the orientation of the crystal to the plate can be varied. In conducting a test the crystal is lowered into the liquid air and, after effervescence has subsided, the metal plate is moved very slowly towards the crystal. If the crystal is pyro-electric, it is attracted to the plate by the induced charge and clings to the plate on withdrawal. The position of the electric axis can be determined by rotating the crystal and finding the part which adheres most strongly.

Micro-Chemical Methods.²—One of the chief advantages of micro-chemical methods is that they can be carried out very much more quickly than the more usual macro-methods, owing to the fact that the quantity of sample taken is only a few mgm., and therefore the time occupied in filtering, washing and igniting precipitates etc. is much reduced. A further advantage is that economies can be effected in the quantity of reagents, gas and electricity used and in the bench space occupied by the apparatus. The degree of precision attainable by micro-chemical methods is indicated by the fact that a rock analysis carried out on a 10 mgm. sample should give results

¹ "On a New Method of Detecting Pyro-Electricity." *Mineral. Mag.*, 22, 1931, p. 591.

² H. V. A. Briscoe, "Micro-Chemical Methods Suitable for General Analytical Practice." *Inst. Chem. Great Brit. and Ireland Bull.*, 1934.

accurate to ± 0.2 per cent. for each element. The two most important pieces of apparatus required are a micro-balance and a microscope and apart from these two the remaining items are relatively inexpensive. The balance (*Fig. 19*) is usually of the type devised by C. F. Kuhlmann, sensitive to 0.01 mg., and carries a maximum load of 20 gm., while the microscope may

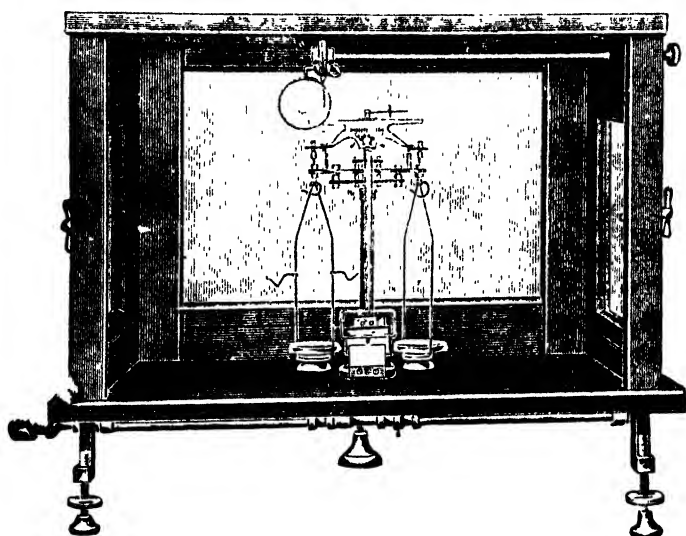


FIG. 19. Micro-Analytical Balance.

be of any reliable pattern giving magnifications up to $\times 250$. A rotating stage and crossed Nicol prisms are an advantage but are not absolutely essential. A full description of the technique of quantitative inorganic micro-analysis and the application of "spot reagents" to qualitative work will be found in the references given at the end of the section and only general features will be dealt with here.

Quantitative Methods.—The filtration of precipitates is accomplished with the aid of filter sticks consisting of glass tubes on the ends of which are sealed mats of sintered glass,

porcelain or spongy platinum. One of the principal sources of error in ordinary gravimetric analysis lies in the loss occasioned by transference of precipitates from a beaker to a crucible. This error is avoided in micro-chemical work by adopting the following procedure. The combined weight of a crucible and a filter stick is ascertained, following which a solution (4 ml.) of the substance to be analysed is prepared and placed in the crucible and the necessary reagents etc. added. The filter stick is then inserted in the solution, mat downwards, and the precipitate, usually about 3 mgm., filtered and washed by suction. Finally the filter stick and crucible are dried and

again weighed. If it is desired to deal with larger amounts of precipitate (25 mgm.) and solution (50 ml.), a Pregl type of micro-filter is placed in a suitable suction flask and the transference of the solution from the reaction vessel, together with the washing of the precipitate, effected by suction through a tube attached with a cork to the top of the filter (Fig. 20).

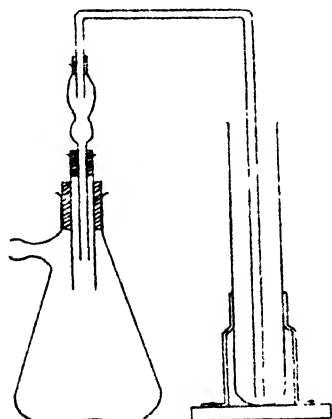


FIG. 20. Pregl Micro-Filtering Apparatus.

For adding specified amounts of reagents small tubes with fine jets are substituted for measuring cylinders, while the evaporation of solutions is very quickly accomplished over micro-burners in

less than one-tenth of the time required by macro-methods. Precipitates are dried by gently warming in a partial vacuum in special tube driers of the Pregl or Pichler type, in which a very slow current of dry air is drawn over the crucible. With porcelain crucibles and filter sticks, ignitions may be carried out by placing them in a larger crucible and igniting directly over a flame or alternatively micro-muffles may be employed.

Volumetric Micro-Work.—The alternatives available for this class of work are either to use normal concentrations and employ micro-burettes or to use very dilute concentrations (N/500) and employ the usual type of burette. Frequently a combination of both methods is found most convenient. A

common type of burette is the automatic, delivering 10 ml. and graduated in 1/50th ml. Micro-burettes for use with N/10 solutions usually have no tap and normally consist of a straight graduated tube drawn out to a capillary holding up to 5 ml. of liquid. Attached to the top of the burette by a cork is a fine capillary regulating the admission of air and consequently the rate of outflow from the burette. Small tubes, crucibles, or even microscope slides are used as titrating vessels. Micro-pipettes usually have a capacity of 0.1-2 ml. and are commonly made by the analyst from ordinary capillary tubing. They can only be employed for liquids of the same viscosity as the calibrating liquid.

Qualitative Methods.—Precipitates are ashed in small platinum boats or on pieces of foil; fusions are carried out on platinum wire and digestions either in small crucibles heated with a metal hot plate or in special glass vessels. Precipitates may be separated by methods similar to those adopted in quantitative work or by a micro-centrifuge. In the latter case, the supernatant liquid is transferred in a capillary tube. When it is necessary to filter a precipitate produced on a microscope slide, a capillary 1 mm. in diameter is pressed on a small piece of moist filter paper and the latter moved into the drop causing the filtrate to rise in the tube. With a comparatively coarse precipitate the filtrate may be separated simply by placing the tip of a very fine capillary on the precipitate. Should the precipitate accidentally enter the capillary tube, the latter is centrifuged and the tip containing the precipitate removed. Reagents are employed in the form of concentrated solutions in order to avoid excessive dilution and are added with fine capillaries or in the loop of a platinum wire; mixing is carried out either with a small rod or by centrifuging. Where the crystalline form of a precipitate has subsequently to be examined under the microscope, the reagent is added at the edge of the solution in order that the crystals may form slowly and develop their characteristic habit. Alternatively crystallisation may be delayed by adding glycerol to the solution.

Spot Tests.—A high degree of manipulative skill is required for the successful recognition of elements by the crystalline form of their salts and in late years "spot" tests have become increasingly popular. These may be carried out on a

filter paper or a spot plate. In the first instance, the solution of the reagent usually in a volatile solvent is spread on to a filter paper to which one drop of the test solution is applied. A spot plate is normally employed only where the test is so highly sensitive that a blank cannot be obtained when the filter paper is used. Examples of spot reagents are: dimethylglyoxime for nickel, para-nitrobenzylazoresorcin for magnesium, rubeanic acid for copper and di-phenylthiocarbazon (dithizone) for lead. Reactions with gases are carried out in specially designed stoppered tubes.

Sampling.—Materials capable of being finely ground are sampled in the manner normal for macro-methods, but ground still finer. In certain instances the necessity for grinding may be obviated altogether; thus, if a silver coin is rubbed once on unglazed porcelain, the quantity removed is sufficient to be detected by the use of the reagent para-dimethyl benzylidene rhodamine. If the sample possesses a smooth surface a gelatin film impregnated with the reagent may be applied, when spots will develop if the substance tested for is present. Alternatively, the gelatin may be impregnated with a solvent for the substance and the spots developed in a bath of the reagent. As an instance of the latter process, copper may be detected by soaking the gelatin in ammonia and subsequently immersing in an aqueous alcoholic solution of rubeanic acid.

For those interested in the subject further details on qualitative and quantitative micro-analysis will be found in the paper previously mentioned and in the publications cited below.¹

¹ "The B.D.H. Book of Reagents for Spot Tests and Delicate Analysis." (British Drug Houses, London), 1937.

F. Emich, "Micro-Chemical Laboratory Manual." translated by F. Schneider. (Chapman and Hall, London), 1932

E. Sucharda and B. Bobranski, "Semi-micro Methods for the Elementary Analysis of Organic Compounds." translated by G. W. Ferguson. (Gallenkamp, London), 1936.

Catalogue No. 103A, 8th Ed. (Gallenkamp, London).

F. Pregl, "Quantitative Organic Micro-analysis." translated by M. Daw (J. and A. Churchill, London), 1937.

E. M. Chamot and C. W. Mason, "Handbook of Chemical Microscopy." (Wiley, New York), 1930 and 1931.

C. A. Mitchell, "Recent Advances in Analytical Chemistry." II ed. Section on Micro-Chemistry by J. W. Brown (J. and A. Churchill, London), 1931.

F. Feigl, "Qualitative Analyse mit Hilfe von Tüpfelreaktionen." Akademische Verlag., Leipzig, 1931, translated by J. W. Matthews (Crosby, Lockwood, London), 1937.

CHAPTER VII.

MICROSCOPICAL EXAMINATION OF SEDIMENTS.

The Petrological Microscope—Special Equipment—Stereoscopic Binocular Petrological Microscope—Microscope for Particle Shape and Size Measurement — Microscope Accessories: Microscope Lamp — Dark-Ground Illumination—Eye-Piece and Stage Micrometers—Spectroscopic Attachment—Compensators—Systematic Examination of Sedimentary Rock Minerals under the Microscope—Refractive Index—Thickness of Grains—Thickness of Rock Sections—Inclusions—Pleochroism—Isotropism—Birefringence—Extinction—Interference Colours—Relative Retardation and Vibration Directions—Interference Figure—Determination of Sign—Optic Axial Angle—Dispersion of Optic Axes—Diagnosis of Minerals by Refractive Index (Immersion) Method—Refractive Index Liquids—Summary of Optical Properties of Sedimentary Rock Minerals—Difficulties in Identification of Detrital Mineral Aggregates under the Microscope—Rock Fragments—Composite Aggregates—Use of Coloured Light in Petrographic Work—Minerals Masked by Alteration Products.

The Petrological Microscope.—Opinions probably differ more on the subject of the most suitable microscope for petrographic work than on any other piece of apparatus designed to aid analysis of rocks and minerals. For this reason no useful purpose would be served here in recommending any particular instrument for the work discussed in this volume. On the other hand, whatever instrument is chosen, it should at least embody the following as its essential basic equipment, which the author has found indispensable to his own work :—

(1) A cross-webbed *Ocular* with adjustable eye-lens. A slot should be cut in the ocular tube at 45° to the cross-wires to take a quartz-wedge, eyepiece micrometer etc.

(2) A *Bertrand lens*. Some instruments are fitted with two, one to focus and another on a plate which is also recessed to accommodate a *Klein Quartz Plate*. Though not indispensable, the Bertrand lens is often a useful accessory.

(3) An *Analyser*, preferably sliding in and out of the body-tube, or it may be mounted over the ocular.

(4) A *Slot* with dust-proof cover, set at 45° to the cross-wires in the ocular below the analyser in the body-tube.

(5) A *Centring Nosepiece* (double or triple) to accommodate objectives.

(6) *Objectives*. A 1 in. and $\frac{1}{4}$ in. or $\frac{2}{3}$ in. and $\frac{1}{8}$ in. are recommended for normal work. Other objectives recommended are listed on p. 158.

(7) A *Rotating Stage* divided into 360° reading by vernier to 5 minutes.

(8) A *Convergent System* (sub-stage condenser) mounted in an *Iris Diaphragm*, attached so that it can be swung in and out of the optic axis of the instrument.

(9) A *Polariser* so mounted that it can be swung in and out of the optic axis of the instrument and fitted with spring catch to indicate zero position.

(10) A double *Mirror*, one side concave for convergent light etc.

(11) *Fine Adjustment (Micrometer Screw)* with milled head divided to read to 0.01 mm. Sometimes a differential screw to read to 0.001 mm. is preferred.

Fig. 21 illustrates such a microscope entirely suitable for all ordinary work and with its components labelled, so that the novice should have no difficulty in appreciating the functions and positions of the vital parts concerned. It is of the utmost importance that before any serious work is begun the microscope should be thoroughly understood, its potentialities mastered and every adjustment familiarised; this statement may appear elementary, but it is remarkable how many difficulties in diagnosis or in optical determinations, imagined by students, can be explained by their inability to use their instrument to the full extent of its powers. In cases where personal instruction is not immediately available, manufacturers' catalogues usually convey very full information on any particular model, while such books as C. Beck's "*The Microscope*" (1938) will be found of value.

Special Equipment.—The petrological microscope above described will be found to fulfil all the functions demanded of it in normal petrographic work, *i.e.* magnification, physical and optical measurements; this suffices for ordinary investigations,

but where special work is involved, *e.g.* a high degree of precision in optical measurement, photomicrographic reproduction etc., certain modifications of design and/or refinements

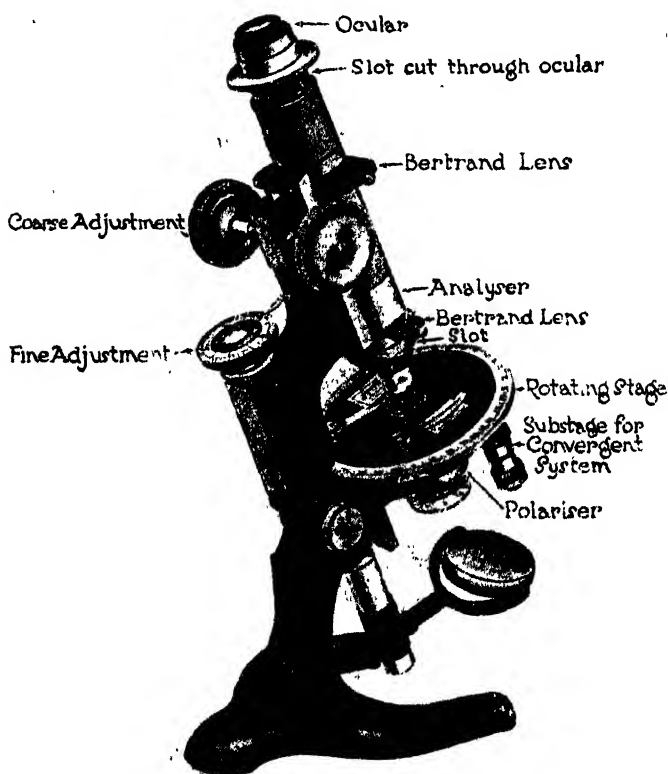


FIG. 21 Petrological Microscope.

in attached accessories are desirable; among those most in use to-day may be mentioned the following:—

Anastigmatic Body Analyser.

It is claimed for this type of analyser that it eliminates any astigmatism and consequent lack of definition of details of the object under examination; this is important when photographing such objects in polarised light; it is further claimed

that such an analyser eliminates all distortion of the image. The principle of the anastigmatic body analyser is that of a tube analyser fitted with a system of correction lenses. It may be observed that the amount of astigmatism discernible with the ordinary tube analyser fitted into a long body-tube (at least 200 mm.) is not normally very great.

Analyser Mounted over Ocular.

One advantage of this is that the analyser prism can be revolved independently and the degree of rotation read from a divided circle which has a zero stop, as is normal with the polariser. This is advantageous in certain optical measurements, but it has the disadvantage that it limits the field of view, especially when high power magnification is employed and further it is much more fatiguing to the eye.

Synchronous Rotation of Analyser and Polariser.

This has certain manipulative advantages over the independent operation of the nicols, but in some instruments it is impossible to rotate them completely through 360° ; usually the maximum amount is 240° . A "Dick" microscope, however, permits complete and continuous rotation of the nicols.

Body-Tube of Large Diameter.

This is necessary in photographic work where the tube has to accommodate ordinary photographic lenses.

Rotating Mechanical Stage.

A rotating stage fitted with fully graduated mechanical movements is of the greatest use in searching mineral concentrates and fixing the position of any one grain within the mass. It is also exceedingly useful where grain counting is involved.

Stereoscopic Binocular Petrological Microscope.—This type of microscope has come greatly into favour during the last few years with those engaged on petrographic and especially micro-palaeontological researches. There had long been a demand for an instrument combining the advantages of stereoscopic relief with polarised light, a demand indirectly accentuated by the eye-fatigue occasioned by constant examina-

tion of many hundreds of slides, the lot of those concerned with such intensive work where the ordinary monocular pattern is in use. In this connexion, some remarks by M. I. Goldman on "*Testing and Adjusting the Binocular Microscope*" etc., are particularly apposite.¹

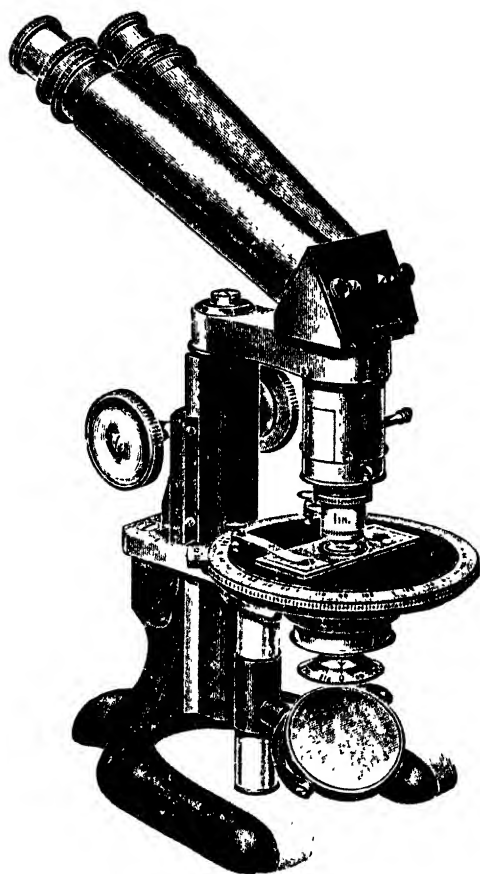


FIG. 22. Stereoscopic Binocular Petrological Microscope.

In the accompanying illustration (*Fig. 22*) a British pattern of Stereoscopic Binocular Petrological Microscope is shown, the chief features of the instrument being the range of

¹ *Bull. Amer. Assoc. Petrol. Geol.*, 9, 1925, p. 175.

objectives possible ($\frac{3}{4}$ in.— $\frac{1}{2}$ in., $\frac{1}{4}$ in., or $\frac{1}{8}$ in. if in short mounts), the adjustability of the draw-tubes containing the oculars to the correct inter-ocular distance of the observer and a special low power achromatic condenser designed for micro-palæontological work, having a long working distance and yielding good dark ground illumination. The author has used such an instrument with much success with sands, heavy residues, dry air mounts of *foraminifera*, also mineral flakes immersed in refractive index media etc. It is an unquestioned advantage where continued investigation of a long series of microscope slides is entailed.

As this instrument may take more understanding than the monocular pattern, the following notes may help the student in its use :—

(a) In the investigation of well-samples, large fragments of rock, fossils, individual minerals and all opaque materials, dark ground illumination is essential and may be secured by placing either a white or black card (depending on the colour of the substance examined) on the stage and employing strong incident light, preferably from an illuminator attached to body tube of the instrument (see p. 161).

(b) Everything depends on the correct adjustment and intensity of illumination, whether transmitted or incident, a matter of much greater importance than with the simple pattern microscope. If the daylight available is not sufficiently strong, use a 100 watt gas-filled "daylight" type electric lamp. With transmitted light, the rays should fall directly on to the concave mirror, care being taken to adjust so that the filament is not reflected in the instrument. With incident light, allow the rays to fall obliquely on to the object on the stage, unless special dark-ground illumination apparatus is employed, when this adjustment will be made automatically.

(c) The 1 in. objective normally suffices for all ordinary work with this instrument, but the higher power ($\frac{1}{2}$ in.) can be used when the object is not too large, care being taken not to scratch the objective when racking down to focus. For examination of thin sections, transparent objects, detrital mineral grains mounted on glass slips etc., with transmitted white light and 1 in. objective, the condenser is not required and the polariser should be swung out of the optic axis until it is required for polarised light determinations. *Where the high power objective is being used with transmitted light, it is essential to employ the condenser, otherwise the illumination will not be sufficiently strong, or may be partially cut off.*

(d) Focusing is in all cases effected by the coarse adjustment, actually quite a sensitive mechanism, also to some extent by the oculars independently.

(e) For interference figures in rock-minerals with this instrument, insert the condenser, swing in the polariser, use the high power objective, push in the analyser and remove both oculars : observation through either ocular-tube with the eye a little distance away from the aperture and, if necessary, shifted slightly to the right or left, will reveal the desired figure on a small scale. Determination of sign with a quartz-wedge is carried out in the normal manner by inserting it in the slot at the bottom of the

body-tube underneath the analyser; the wedge is thus placed at 45° to the cross-wires; see p. 173.

(f) Should there be any trouble with the nicol prisms owing to excessive heat of the tropics, detach both polariser and analyser and send them back to the manufacturers. This possibility is very remote indeed and can be largely avoided by keeping and using the instrument, or any microscope for that matter, in a cool room during this time. *On no account attempt to repair the prisms without expert advice.*

Microscope for Particle Shape and Size Measurement.—

When working on fine sediments or crushed rock powders of all descriptions, especially where any check of results of mechanical analysis by microscopical means is desired, it is advantageous to employ an instrument specially designed for the purpose. One in constant use at the author's laboratories, which has proved invaluable in the course of particle size determinations, embodies the following features:—

- (1) Standard horseshoe type base, very rigid and firm, curved limb for easy lifting, 3 cm. diameter body-tube. The stand is steady in all positions from vertical to horizontal, the latter important when projecting slides of particles on to a screen for measurement (p. 116).
- (2) Coarse and fine adjustment.
- (3) Rotating stage (with thumb-screw clamp for fixing if necessary) graduated in 360° with vernier reading to 5 minutes, fitted with clips (removable) to hold slide, also with sockets to receive special form of stage micrometer (p. 161).
- (4) Iris diaphragm carrying a condenser.
- (5) Double mirror, one plane, the other concave for convergent light and high power magnification.
- (6) Interchangeable oculars: (a) $\times 6$ with co-ordinate ruling, the lines being 0.1 mm. apart; (b) $\times 6$ with ordinary cross-wires; (c) $\times 20$ (12.5 mm.) for specially high power work.
- (7) Objectives 1 in. (n.a. 0.25); $\frac{1}{2}$ in. (n.a. 0.50); $\frac{1}{4}$ in. (n.a. 0.80), $\frac{1}{8}$ in. (n.a. 0.85); 1-12 in. oil immersion (n.a. 1.30).
- (8) Eye-piece and stage micrometers (p. 161).

With this instrument the following magnifications can be secured (body-tube length 160 mm.):—

Objective.	N.A.	Ocular.	Magnification.
1 in.	0.25	$\times 6$	37
1 in.	0.25	$\times 20$	142
$\frac{1}{2}$ in.	0.50	$\times 6$	86
$\frac{1}{2}$ in.	0.50	$\times 20$	355
$\frac{1}{4}$ in.	0.80	$\times 6$	184
$\frac{1}{4}$ in.	0.80	$\times 20$	685
$\frac{1}{8}$ in.	0.85	$\times 6$	279
$\frac{1}{8}$ in.	0.85	$\times 20$	950
1-12 in.	1.30	$\times 6$	555
1-12 in.	1.30	$\times 20$	2010

Such a range of magnifications is sufficient for all ordinary work on fillers, rock flour, finely suspended mineral matter in asphalt etc.

Accessories to Microscope Work.

Microscope Lamp.—There are various forms of these on the market, mostly for electric light. The essential factor in artificial illumination for microscopy is that the light, while being brilliant, must be uniform, properly diffused and must not reflect the lamp filament. This is accomplished generally by interposing a textureless ground screen or white matt glass in front of the lamp or one made of a special blue glass if "day-light" illumination is preferred.



FIG. 23. Intensity Lamp.

Two types of lamp are recommended, one (*Fig. 23*) for projection work consisting of a 24 watt gas-filled lamp, properly housed in a light-tight, well ventilated case and in other respects conforming to the above requirements, supported on a firm stand and adjustable to varied positions; the other (*Fig. 24*) in which light from an

electric bulb is made to pass through a cylindrical, clear glass rod ("speculum"), has the advantage that the illuminant has uniform intensity and is circular in shape, the former being alterable within wide limits without change of quality. This form of lamp has been developed by F. Welch and is fully described.¹ It is especially suitable for microscopical work with artificial transmitted light where daylight is inadequate.

Provision for monochromatic light may be made by the simple method of suspending a bead of sodium salt in a platinum wire loop held in a bunsen burner. A more scientific method is to employ a lamp in which a glow discharge takes place in sodium vapour, such a lamp being coupled to a suitable rectifier to supply heating current to the filament.²

¹ *Journ. Roy. Micros. Soc.*, 50, 1930, p. 34.

² Phillips Industrial, London.

Dark-Ground Illumination.—A recently introduced illuminator, consisting of a $3\frac{1}{2}$ volt lamp and an aplanatic condenser, carried in a tube easily attachable to the nose of the microscope, is a great advance on previous lamps of its kind and permits accurate control of top lighting for all purposes (*Fig. 25*).¹

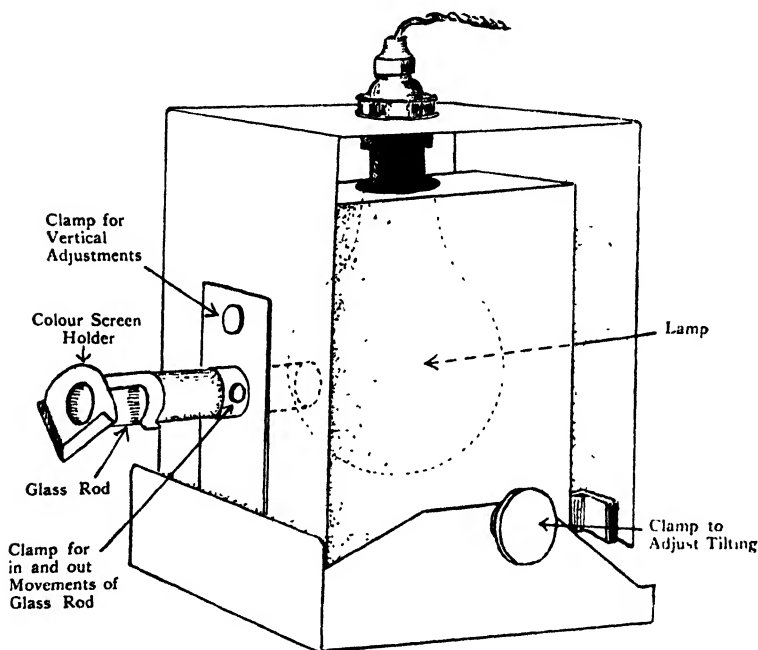


FIG. 24. Microscope Lamp. (After F. Welch, *Journ. Roy. Micros. Soc.*, 50, 1930, p. 34-37.)

Eye-Piece Micrometer.—Two types are normally used for particle size measurement, one in which a scale is reproduced on a 21 mm. glass disc, mounted in vulcanite holder to pass through the slotted ocular of a petrological microscope, or simply as the disc to drop on to the stop of any particular ocular; the other similarly mounted, or unmounted if preferred, with co-ordinate ruling.

¹ J. Swift and Son, Ltd., London.

Stage Micrometer.—A special form of auxiliary stage micrometer has been constructed at the author's suggestion by J. Swift and Son, Ltd., London, embodying the principles of expeditious and accurate measurement of particle size to 0.001 mm. It can be employed on any microscope irrespective of body-tube length, ocular or objective used and will be found invaluable in all determinations associated with mechanical analysis (*Fig. 26*).

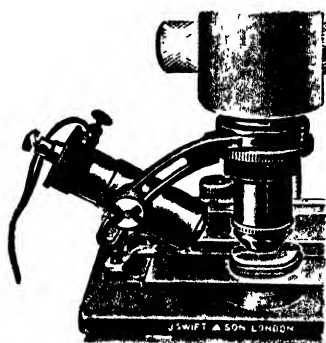


FIG. 25. Dark Ground Illuminator.

“The apparatus, which is placed upon the stage of the microscope, consists of a supplementary stage, which is moved in a dovetailed slide by a micrometer screw of 1 mm. pitch. This screw carries a drum with one hundred divisions, each the equivalent of .01 mm. of the object; these divisions, in their turn, are sub-divided by means of a vernier to .001 mm. The range of the screw is 20 mm., so objects up to this size can be measured; complete revolutions of the screw, each 1 mm., are recorded on a scale on the edge. Measurement is made against a line or web in the ocular.

In use, the slide bearing the object to be measured is placed on the micrometer stage and focussed in the ordinary manner. By means of the screw, one edge of the particle to be measured is brought against the web or line in the ocular and the reading of the scale and drum noted; the movement is then continued until the other edge is coincident with the web, when

the difference between the reading of this position and the first gives the actual length of the object.

The usual and most satisfactory manner of attaching this micrometer stage to the microscope is by means of a small knurled head with a standard 6 B.A. thread, which screws into a tapped hole in the main stage; several models of Swift microscopes are provided with this tapped hole as standard practice. . . . Instead of this method it may be held sufficiently rigidly on the main stage by means of small pellets of "Sira" wax or plasticine, to accommodate which there are four small recesses on its under side; for this purpose a small

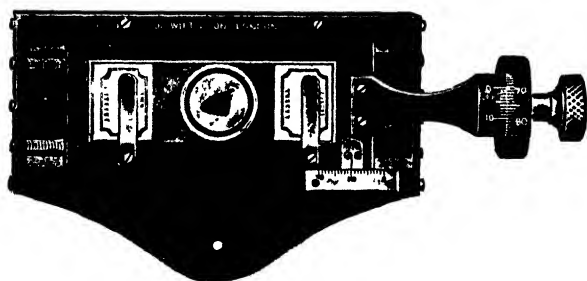


FIG. 26. Auxiliary Micrometer Stage.

ball of wax, slightly more than enough to fill it, should be pressed into each recess, the micrometer placed in the correct position on the main stage and the two then firmly pressed together.

The use of a co-ordinate ruling in the ocular in conjunction with the micrometer stage still further facilitates measurements of average particle size. A very convenient ruling is one which gives squares of approximately .01 mm. side when used with a $\frac{1}{8}$ in. objective on a standard length body-tube. The ruling is calibrated with the micrometer stage and measurements are carried out by estimating the area covered by the particle in squares and fractions of squares. Fresh particles may be brought into the field by turning the screw of the stage."¹

¹ From notes accompanying this micrometer.

Spectroscope for Petrological Microscope.—A simple form of spectroscopic attachment (*Fig. 27*) is usefully employed with a petrological microscope in which a slotted ocular is available, when examining concentrates for rare earth minerals, *e.g.* monazite. This consists of a prism A mounted to fit over the ocular and a brass plate B for insertion in the slot. The plate is provided with an adjustable slit, variable in length by a slide having a V cut at one end. The width of the slit can be controlled by means of a thumb-screw at the right end of the plate.

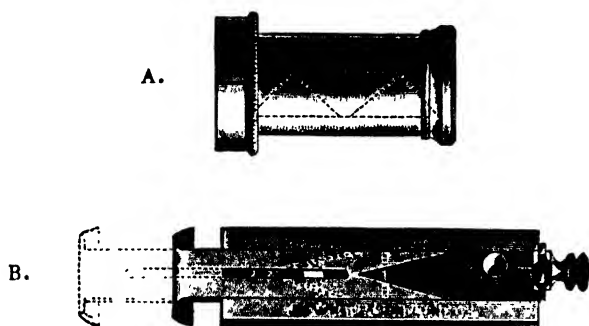


FIG. 27. Spectroscopic Eyepiece Attachment

A. Prism to fit over ocular of microscope.

B. Brass plate with adjustable slit for insertion in slot.

Compensators.—For precise optical work a mica or gypsum plate and a quartz wedge are essential. The mica plate, sometimes known as a "quarter wave plate," is made in such a way that retardation of one of the two rays into which it splits the light is $\frac{1}{4}$ wave length behind the other. The mica is cut in the form of a rectangle, the edges of which are parallel to the two directions of vibration and suitably mounted on a glass slide, usually half the width of the ordinary 3 in. \times 1 in. slip.

The gypsum or selenite plate, sometimes known as a "unit retardation plate," is cut in a similar way from a well cleaved, flawless crystal. The "cleavage flake" is chosen which gives 1st order red; this is suitably cut and mounted as

in the case of the mica plate and used to produce a retardation of one wave length.

The quartz wedge is constructed from specially selected quartz crystal ground down parallel to the crystallographic *c*-axis or optic axis, in the form of a wedge, one end being as thin as possible, the other of a thickness which ensures that at least five "orders" of colour are shown by the whole wedge

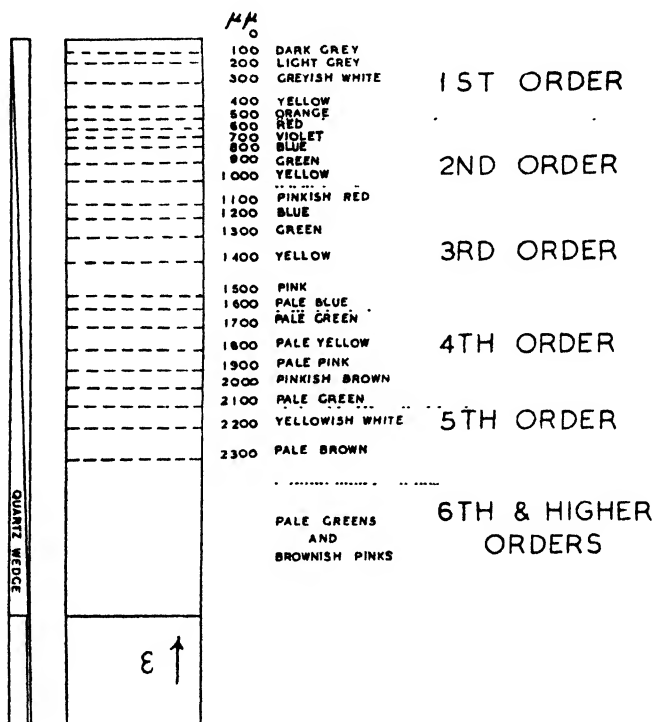


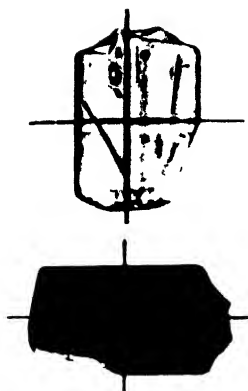
FIG. 28. Quartz Wedge.

when viewed between cross nicols. These colours take the form of bands traversing the wedge at right angles to its length, each band corresponding to different degrees of retardation of the light as it is transmitted through different thicknesses of the quartz unit. Such a wedge is best calibrated along its length at appropriate places to denote relative retardation (in $\mu\mu$) and order limits. It is normally mounted in

A



B



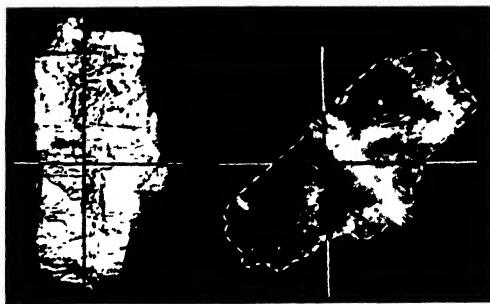
A, B — PLEOCHROISM
 Tourmaline, Dumoitierite
 X B — Vibration direction of polariser E-W

C



C — PARALLEL EXTINCTION
 Quartz, 90° position 45° position
 Note — Outgrowth *not* in optical continuity with nucleus.

D



D. OBLIQUE OR INCLINED EXTINCTION.
 Kyanite 90° position 45° position

To face page 165.

PLATE 4

a similar manner to that of the mica or gypsum plate; as thus supplied, its length coincides with the slow direction (ϵ) of light vibration and this is frequently indicated by an arrow engraved on the wedge parallel to its length, followed by the letter ϵ (*Fig. 28*).

An alternative to this convention is the J. W. Evans double quartz wedge which consists essentially of two wedges mounted side by side, but so ground that one exhibits the slow direction (ϵ), the other the fast (ω) in parallel position on the mount. Such a wedge shows simultaneously the effect of insertion at 45° in two directions.

The Klein plate, which is not often employed in petrological work where nicols prisms are properly calibrated, is a means of determining accurately that the polariser and analyser are properly crossed with maximum darkness ensuing. It consists of a section of specially selected quartz crystal cut at right angles to the crystallographic c -axis or optic axis and of the necessary thickness to give a violet tint; this colour changes perceptibly with the slightest rotation of either or both of the nicols prisms.

Systematic Examination of Sedimentary Rock Minerals under the Microscope.—A systematic investigation of sedimentary rock minerals is strongly recommended, until by experience the student has become proficient in the art of recognising and discriminating between associated species. The plan of procedure may be summarised as follows:—

1. *With transmitted white light, low and high power objectives.*

- (a) Transparency, translucency or opacity.
- (b) Colour.
- (c) Habit. Presence or absence of crystal faces.
- (d) Shape. Angular, subangular, rounded.
- (e) Size. Estimate or measure with eyepiece or stage micrometer.
- (f) Fracture. Uneven, conchoidal etc.
- (g) Parting. Linear or irregular.
- (h) Cleavage. Principal and subordinate directions.
- (i) Abrasion, degree of. Pitting or other surface features.
- (j) Refractive Index. Compare with Canada balsam (1.55).
- (k) Thickness of grains.
- (l) Inclusions.

2. *With reflected light against dark background to slide (dark ground illumination).*

- (a) Lustre. Adamantine, metallic, submetallic, vitreous, resinous etc.

3. *With transmitted light, polariser only inserted.*
 - (a) Pleochroism. Presence or absence. Weak or strong. Colour change with orientation of grain. "Twinkling" as indicative of carbonates (rotation of polariser only).
4. *With transmitted light, crossed nicols.*
 - (a) Isotropism or anisotropism.
 - (b) Birefringence.
 - (c) Extinction. Straight or oblique; in latter case determine angle.
 - (d) Interference colours: order etc. (with quartz wedge or other device).
 - (e) Relative retardation and vibration directions (with quartz wedge, gypsum plate etc.).
5. *With convergent light, high power objective, crossed nicols and Bertrand lens.*
 - (a) Detection of interference figure: uniaxial or biaxial.
 - (b) Determination of the sign of the crystal by means of a quartz wedge, gypsum or mica plate.
 - (c) Optic axial angle.
 - (d) Dispersion of optic axes.

NOTES.

1 (a)-(i). Most of these physical determinations are straightforward. Translucent minerals can frequently be rendered more transparent by inserting the condenser; similarly opaque minerals may be rendered slightly translucent on thin edges, e.g. sphalerite, chromite. Cleavage may be an important diagnostic property, especially in thin sections, e.g. amphiboles and pyroxenes, where two sets of cleavage lines may intersect at given angles. Many detrital minerals tend to exhibit conspicuous cleavage, e.g. kyanite, topaz, calcite, fluorite. Degree of abrasion and shape of grains are important factors in the study of heavy mineral residues for correlation (p. 460).

1 (j). *Refractive Index.*—The most common method of determining relative refractive index is that known as the method of central illumination or Becke's "White Line" method, generally applicable, but particularly to minerals in thin section and to platy detrital grains (Fig. 29). The test is as follows:—If the mineral under observation has a *higher* R.I. than a contiguous mineral or mountant such as Canada balsam (R.I. 1.540) then on *raising* the objective a "white line" (i.e. apparent periphery or boundary of the mineral) will contract inwards, i.e. away from the contact substance or medium of lower R.I. (N.B.—A good mnemonic is to connect in the mind the words "high" and "raise".) Conversely, if the mineral under observation has a *lower* R.I. than a contiguous mineral or mountant, then on *raising* the objective the "white line" will expand outwards, i.e. into the substance or mountant of higher R.I. Fig. 29 makes these conditions clear. If the mineral and contiguous substance or mountant have identical refractive indices, the contact is practically invisible and the "white line" effect is reduced to a minimum. Lowering instead of raising the objective reverses the above effects. Use the concave mirror when making the test. In some cases manipulation of the iris diaphragm is advantageous. Do not, however, use the condenser. Another method is that of oblique illumination, or Schroeder Van der Kolk's method. This requires some degree of skill to effect successfully and is carried out with isolated grains or mineral fragments, either mounted in Canada balsam or immersed in a solution of known R.I. For a description of this method see p. 180.

1 (k). *Thickness of Grains.*—This measurement is generally carried out on unmounted material. Make a mark on a glass slip with a diamond and focus the mark with the microscope. Place the grain over the mark and focus its upper surface (turn micrometer screw in same direction throughout). The difference in readings gives the thickness required. Another method is to focus the surface of the grain placed over a mark, then focus the mark through the grain; in this case if the refractive index of the mineral is known, $T = nt$, where T = actual thickness, n = refractive index and t = measurement or difference in the two readings of the micrometer screw.

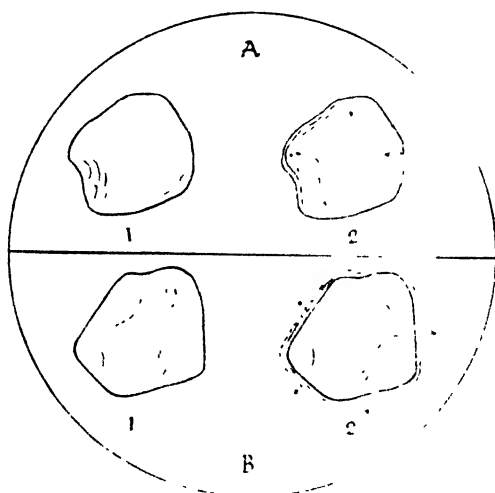


FIG. 29 Diagram to illustrate Becke's Line R.I. Test.

Medium : Canada balsam.

- A. 1. Topaz grain in correct focus
2. Same with objective raised: margin travels inwards.
- B. 1. Fluorite grain in correct focus.
2. Same with objective raised: margin travels outwards.

In the case of mineral grains forming part of a residue mounted in Canada balsam on a glass slip, approximate thickness of a grain can usually be estimated by focusing its lower surface (boundary edge if coloured or translucent) and then its upper surface (centre of grain); the difference between the two readings as recorded by the micrometer screw gives the desired information, allowance being made for the R.I. as before.

Thickness of Rock Sections.—A satisfactory thickness for thin sections is 30μ . Thickness of a mineral slice in microns is equal to the interference colour value (p. 170) divided by 1,000 times birefringence (p. 169). Hence it is necessary to choose a common mineral in the slice, the bire-

fringe of which is known, *e.g.* quartz, $B=0.009$. Examine a number of quartz components in the slice and estimate the highest interference colour (in $\mu\mu$) revealed by comparison with a standard interference or polarisation colour chart, *e.g.* that by W. R. Jones and A. Brammall.¹

Example.—Search of a series of quartz components shows 1st order yellow as highest interference colour value (say) $400\mu\mu$. Hence thickness of slice T (in μ) is given by:—

$$T = \frac{400}{1000 \times 0.009}$$

$$T = 44\mu, \text{ or } 0.044 \text{ mm.}$$

Where slices are of uniform thickness, determined as above, associated minerals may be diagnosed with reference to their birefringence values (p. 613). This is particularly useful when dealing with well-made rock slices, where the quartz components are all exhibiting 1st order grey interference colours. The problem is not quite so easy, however, when the slice is of varying thickness (as attested by quartz particles of high 1st order or even 2nd order colours), especially in central portions of rocks which have presented difficulty in slicing.

1 (l). *Inclusions.*—The study of inclusions in mineral grains is important from a crystallographic standpoint and also it is frequently of diagnostic value. Inclusions should be classified not only as regards nature, but also according to frequency, orientation, size etc. Inclusions may be solid, *i.e.* definite mineral species; rarely liquid; or may be gaseous or air-filled chambers; or often glass. Search, if necessary, with the highest power magnification available.

2 (a). For observations with dark-ground illumination, refer to paragraphs (a), (b) and (c) on p. 157.

3 (a). Direction of maximum absorption should be carefully determined, also whether fast or slow: see below, § 4 (e). Pleochroism is best seen by rotating the nicol rather than the stage. The use of the high power objective and convergent light is extremely helpful where the phenomenon is only weakly displayed. Note the diagnostic value of "twinkling" in connexion with the rhombohedral carbonates (observed by rotating the polariser only). Pleochroic halos are best investigated with high power objective and the convergent system. (*Pl.* 4, facing p. 165.)

4 (a). *Isotropism.*—The real test of isotropism is to try for an interference figure. Remember that basal sections of certain minerals will appear isotropic between crossed nicols, but may still give interference figures, hence such minerals are *not* isometric, *e.g.* anatase, tourmaline, quartz. Isometric minerals in the absence of strain phenomena are definitely isotropic and cannot possibly yield interference figures.

4 (b). *Birefringence.*—This is particularly important in rock minerals, whether in thin sections or as isolated grains and should be determined correctly wherever diagnosis is doubtful if such determination is at all possible.

Birefringence may be defined as the amount of retardation in velocity between the slow and fast light vibrations per unit distance through a crystal. Such retardation is expressed in micromillimeters ($\mu\mu$). It is numerically represented also by the difference between the two refractive indices of a uniaxial mineral (p. 169), either ϵ (extraordinary ray) being less than ω (ordinary ray) or *vice versa*; with biaxial minerals it is always the difference between the maximum and minimum values of refractive index, *i.e.* $\gamma - \alpha$ ($\alpha < \beta < \gamma$).

¹ Published by J. Swift and Son, Ltd., London.

*Example 1. Uniaxial Mineral. Quartz.*R.I. $\epsilon = 1.553$, $\omega = 1.544$.Birefringence $\epsilon - \omega = 0.009$, or $9\mu\mu$ per micron thickness of slice.Suitable thickness for thin sections = 30μ .

\therefore Total relative retardation due to quartz section 30μ thick = $30 \times 9 = 270\mu\mu$; this is equivalent to 1st order yellowish white interference colour.

*Example 2. Biaxial Mineral. Kyanite.*R.I. $\alpha = 1.712$. $\beta = 1.720$. $\gamma = 1.728$.Birefringence $\gamma - \alpha = 0.016$ or $16\mu\mu$ per micron thickness of slice.Suitable thickness for thin sections = 30μ .

\therefore Total relative retardation due to kyanite section 30μ thick = $30 \times 16 = 480\mu\mu$. This is equivalent to 1st order red interference colour.

The relationship between birefringence, thickness of mineral and interference (polarisation) colour value is given by:

$$B = \frac{I}{T \times 1000}$$

where B = birefringence measured in $\mu\mu$, I = interference colour value (in $\mu\mu$), T = thickness ordinarily measured in microns (μ) or $\times 1000$ in millimeters (mm). Thus it is clear that, knowing any two of these functions, the third may be calculated.

The diagnostic value of birefringence will be obvious from the above considerations, since if this value for a mineral in thin section or of a detrital grain can be fixed definitely, or even if within reasonable limits, reference to a table such as given in Appendix VII, p. 613, will enable the species to be run down with a fair degree of certainty.

Procedure for thin sections is to determine thickness and interference colour value as described on p. 168 and with reference to a polarisation colour scale, using the formula given above. For isolated grains, procedure is necessarily different.

As is well known in work on detrital quartz, for instance, those grains which do not show emergence of the optic axis and are therefore not isotropic, exhibit interference colours generally in the form of concentric coloured bands or rings. These bands correspond to zones of different thickness of the grain, usually increasing from the periphery to the centre. By selecting a prominent colour such as red and noting the number of red rings from the edge to the centre of the grain, reds of the first and second orders may be distinguished or, if sufficiently thick, corresponding third and fourth order pinks may be revealed; the order being thus known may be fixed approximately in terms of its birefringence ($\mu\mu$) and thus thickness calculated as above. It must be admitted that often detrital grains are too variable in thickness or possibly too thick at the centres to reveal lower order colours; alternatively, the natural colour of the mineral may mask the interference tint; in such cases it is not possible to employ this procedure and other methods of diagnosis become necessary.

4 (c). *Extinction*.—Rock minerals *other* than those crystallising in the isometric system and (exceptionally) sections or grains showing emergence of an optic axis, are anisotropic and normally exhibit interference colours between crossed nicols.

Such minerals, apart from occasional abnormalities of monoclinic and triclinic crystals, exhibit extinction ("black-out") at regular intervals of

90° during one complete rotation through 360°. Extinction positions imply coincidence of directions of light vibration in the mineral with those of the analyser and polariser.

"Parallel extinction" ("straight extinction") is when these directions are parallel to crystal face-boundaries, crystallographic axes, cleavage or twin planes. "Symmetrical extinction" implies a position bisecting the angle between two crystal faces, cleavage planes etc. Both forms are exhibited by all tetragonal, rhombohedral and orthorhombic minerals and by those monoclinic mineral sections or grains which parallel the b-axis. (*Pl. 4, facing p. 165.*)

"Oblique" or "inclined" extinction is characteristic of monoclinic (exception above) and all triclinic minerals (in rare cases no real extinction as such may be discerned) and the angle measured between such an extinction position and a prominent crystal boundary, cleavage or twin plane is the "extinction angle" for that particular mineral section or grain. Measurement of the extinction angle is of considerable diagnostic value, e.g. plagioclase feldspars, kyanite, hornblende. (*Pl. 4, facing p. 165.*)

4(d). *Interference Colours*.—The colours of anisotropic minerals (thin sections or grains), when examined in polarised light, result from interaction of fast and slow light vibrations through such minerals, the phenomenon being known as "interference." Such colours are a function of (a) differential velocities of the fast and slow rays and (b) thickness of the section or grain involved. To appreciate the succession of interference colours ranging from 1st to 4th and perhaps higher orders, the best plan is to study a quartz wedge between crossed nicols. This will (if properly made) reveal the colour bands transverse to the length of the wedge, as shown in *Fig. 28*. (See also *Pl. 5, facing p. 172.*)

Methods of determining the order of interference colour:—

- (i) By inspection. Familiarity with rock minerals and optical measurements thereon, both in thin sections and as grains, enables a reasonably accurate assessment of the colour or shades of colour sequence to be made and thus its position in the lower orders fixed. Remember that the natural colour of a mineral, especially in detrital grains and if dark, may make such visual assessment difficult, even erroneous; in such cases more precise measurements should be undertaken if possible.
- (ii) By matching with a polarisation colour scale. Such scales are reproduced in various text books, but most usefully in the pocket scale by W. R. Jones and A. Brammall,¹ which not only shows the sequence of the first four order colours as revealed by crossed nicols but also the corresponding colours revealed with parallel nicols, the latter forming a definite check on identification of the former.
- (iii) By determining relative retardation, i.e. interference colour value, if thickness and birefringence are known ($I = 1000 BT$, where I = interference colour value in $\mu\mu$, B = birefringence (in μ), T = thickness (in μ).
- (iv) By means of a calibrated quartz wedge (*p. 164*). The mineral is orientated in such a position that when the quartz wedge is superimposed by means of the slot in the body-tube of the microscope (between the analyser and polariser), the interference colour of the mineral is lowered in its order until compensation occurs, i.e. grey or black (isotropism), corresponding to positions in the wedge

¹ See p. 168.

and mineral where the relative retardations are the same for both, or have the same numerical value zero. The succession of colours traversed till the black band appears is a measure of the order of the original interference colour of the mineral and with the wedge suitably calibrated this can be closely assessed in most cases. A gypsum or mica plate (p. 163) of known orientation can be used in the same way.

4 (e). *Relative Retardation and Vibration Directions*.—As will be evident from the foregoing notes on birefringence (p. 168) and interference colours (p. 170), relative retardation is the amount of "lag" of the slow ray behind the fast ray in a crystal and may be conveniently expressed as the product of birefringence and thickness, *i.e.* $R = 1000 \text{ BT}$, where R is always expressed in $\mu\mu$, B and T usually in μ . Relative retardation in $\mu\mu$ values corresponds to specific interference colours as revealed under crossed nicols, such values being grouped into 1st, 2nd, 3rd, 4th orders and so on (Fig. 28), and being multiples of $550\mu\mu$.

Determination of relative retardation is made:—

- (i) Approximately by inspection of the interference colour. This is a matter of practice and recognition of the order of the particular interference colour observed. Reference to a polarisation colour scale is desirable,¹ also check of the colour exhibited with parallel nicols as against normal tint with crossed nicols.
- (ii) More precisely with a quartz wedge. Orientate the mineral at 45° to its extinction position. Using a wedge with length slow (e), insert in the slot in the body-tube between the polariser and analyser. The interference colour due to the mineral is either raised or lowered in its order. If raised, the slow directions of the wedge and of the mineral coincide, *i.e.* the slow direction of the wedge is parallel to that of the mineral; the retardation in this case "plus." If lowered, then the slow direction of the wedge and of the mineral are opposed, *i.e.* the slow direction of the wedge is parallel to the fast direction of the mineral; the retardation in this case is determined by using a calibrated quartz wedge and noting the succession of colours traversed till the zero position (black band) is observed, *i.e.* compensation.

A gypsum plate is employed with advantage in cases where there is low relative retardation. Knowing the character of the length of the compensator (usually fast), that of the mineral under examination may be determined by noting whether the colours are raised (fast) or lowered (slow) when the plate is superimposed on the mineral. A mica plate may be similarly used.

5 (a). *Interference Figure (Directions Image)*.—To obtain an interference figure with the ordinary petrological microscope, use the high power objective, convergent system, crossed nicols and Bertrand lens, with really good illumination; a much clearer figure with detrital grains is always procurable by removing the ocular and dispensing with the Bertrand lens. Sometimes the figure is better appreciated by holding the eye a little distance away from the body-tube aperture (ocular removed). It is a good rule to practise with specially cut mineral-sections which give complete figures, carrying out the necessary observations with quartz wedge, gypsum or mica plate on known substances; this familiarises the observer with the phenomena under the best conditions and serves to

¹ See p. 168.

prepare his eye for less clearly defined figures, such as are often characteristic of detrital grains. *This optical property should be thoroughly mastered at the outset: it is an invaluable test in the diagnosis of detrital and many rock-forming minerals.* For interference figures obtainable with the binocular petrological microscope, see p. 157.

The interference figure may be uniaxial (Fig. 30) or biaxial (Fig. 31). Complete normal uniaxial figures are yielded by minerals crystallising in the tetragonal, rhombohedral and hexagonal systems, presenting sections or grains at right angles to the optic axis. Such figures consist of concentric coloured rings (isochromatic lines) surmounted by a black cross formed by the isogyres which does not break up on complete rotation of the stage through 360° . In very thin sections or grains, the

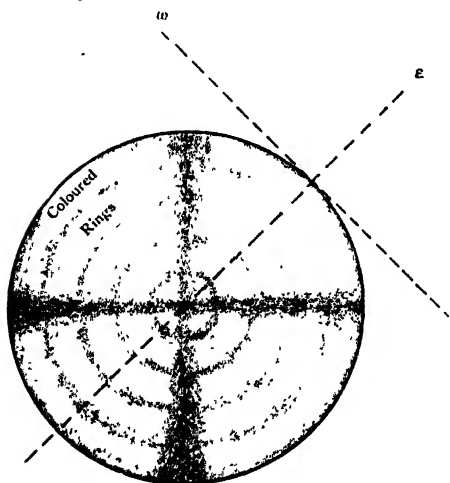
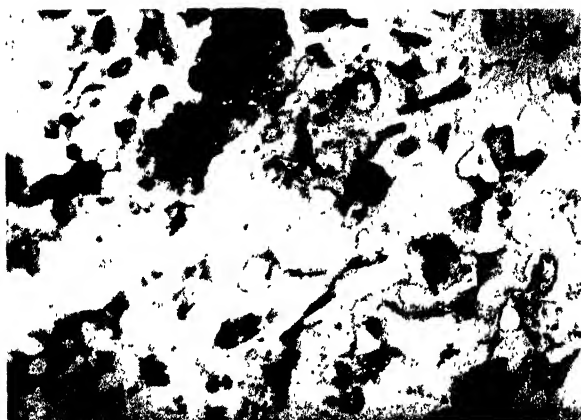


FIG. 30. Uniaxial Interference Figure.

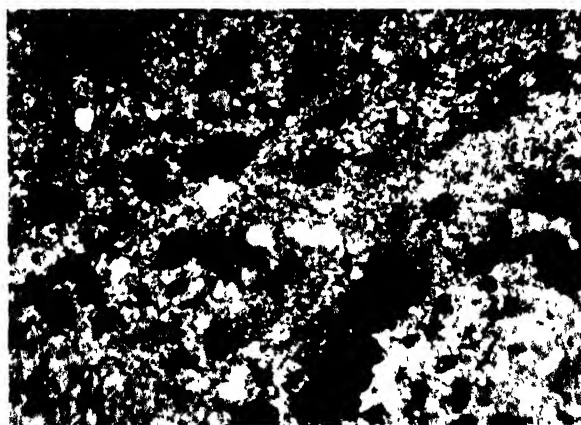
coloured rings may be replaced by a grey-blue background. Biaxial figures are yielded by minerals crystallising in the orthorhombic, monoclinic and triclinic systems, presenting sections or grains at right angles to the acute bisectrix, i.e. the bisector of the acute angle between the two optic axes of such minerals. Such figures assume different complexions according to orientation; in the 90° position (Fig. 31A) the two isogyres unite to form a kind of black cross surmounting coloured lemniscates, similarly for the 0° , 180° and 270° positions. In the 45° , 135° , 225° and 315° positions the "cross" splits up into two curved isogyres opposing each other and convex inwards, surmounting coloured lemniscates as before. Fig. 31C shows this. Both pseudo-biaxial and pseudo-uniaxial figures are sometimes displayed, in the former case a known uniaxial mineral exhibiting a black cross which just "parts" at the centre on rotation, e.g. some varieties of quartz, and in the latter case a known biaxial mineral of exceedingly small optic axial angle only just shows the slight parting of the isogyres in the 45° position, e.g. some varieties of biotite. A "compass-needle" figure, i.e. one isogyre rotating about a central point as the stage is turned, is yielded by the emergence in a crystal section of one optic axis (biaxial mineral), e.g. the basal plane of epidote. Partial figures, common with many detrital flakes, constitute special cases for both uniaxial and biaxial minerals and are sometimes not easy of interpretation.

5 (b). *Determination of the Sign of a Mineral. Uniaxial Mineral.*—This has two indices of refraction, ϵ and ω , corresponding to the extraordinary

A



B



EFFECT OF POLARISED LIGHT.

- A. Chert Hythe (Ragstone) Beds, Ft. Greensand, Borough Green, Kent. *Acropora, transverse*
chert X 35.0
 B. The same. Doubly polarized light.

and ordinary rays respectively. ϵ vibrations are in the plane containing the optic axis, ω vibrations in a position at right angles to this. If $\epsilon > \omega$, ϵ is slow and the mineral is *positive*: if $\omega > \epsilon$, ϵ is fast and the mineral is *negative*. Use a quartz wedge (long direction ϵ slow)¹ and insert it in the slot of the body-tube of the microscope at 45° to the black cross. The effect of the quartz wedge is to cause the cross to break up, apparently into two prominent black "spots," aligned in a definite direction, either parallel or normal to the direction of insertion of the wedge; at the same time the coloured rings are distorted, expanding in one direction (with the "spots") and contracting in the other at right angles thereto. If the cross breaks into two apparent black "spots" in quadrants 1 and 3 (Fig. 32 A) with corresponding expansion of the rings in those quadrants, it will be found that the rings contract towards the

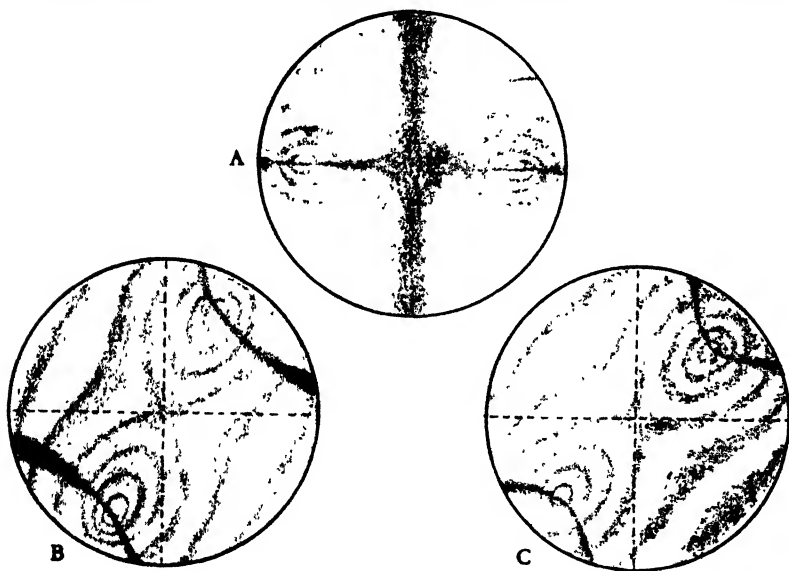


FIG. 31. Biaxial Interference Figures. A. 90° Position; B. $22\frac{1}{2}^\circ$ Position; C. 45° Position.

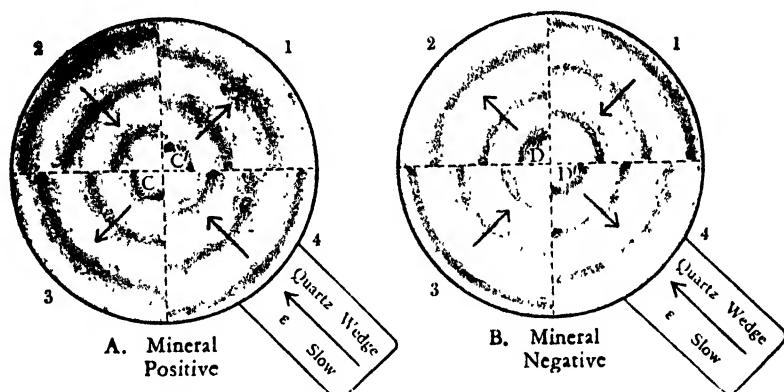
centre in quadrants 2 and 4, *i.e.*, along the line of insertion of the wedge; the mineral is then *positive*. When the opposite movements take place, *i.e.* expansion outwards in quadrants 2 and 4 (along the line of insertion of the wedge) and contraction inwards in quadrants 1 and 3, the mineral is *negative* (Fig. 32 B). A good mnemonic for remembering this is that with a positive mineral an imaginary line joining the two black spots makes a *plus* sign with the length of the quartz wedge as inserted; if

¹ N.B.—Use gypsum plate in cases of low relative retardation, where coloured rings are not apparent or a blue-grey "background" to cross persists. Quartz wedges are also cut with length fast ω ; in this case observations will be reversed (see p. 165).

negative, the line coincides with the length of the wedge and a *minus* sign is suggested.

The foregoing method of determining sign, though empirical, is none the less reasonably accurate, especially where the directions image is complete and clear and in cases where the colours are not easily discernible, which is by no means unusual with detrital grains. Where the image is indistinct or partial and whenever the colours can be interpreted correctly, the more accurate procedure is to note the effect of inserting the quartz wedge (or other compensator) on the colours in the visible quadrants, as when determining order of interference colour (p. 170) or relative retardation (p. 171). Figs. 32 A and B illustrates the two possibilities.

When the mineral is *positive* ϵ is slow; the length of the wedge being slow (ϵ), the coloured rings contract inwards in the direction of insertion



The arrows within the field show the directions in which the coloured rings move as the wedge is pushed into the slot.

Two black spots (indicating compensation) appear at C and C', and develop into quarter circles moving outwards.

The arrows within the field show the directions in which the coloured rings move as the wedge is pushed into the slot.

Two black spots (indicating compensation) appear at D and D', and develop into quarter circles moving outwards.

FIG. 32. Effects of Superimposing Quartz Wedge on Uniaxial Figures.*

of the wedge and expand in a direction at right angles to this. Simultaneously the colours are raised in their order in the two quadrants 2 and 4 in the path of the wedge (where slow direction of the mineral coincides with slow direction of the wedge) and are lowered in the other two quadrants 1 and 3.

When the mineral is *negative* ϵ is fast; the length of the wedge being slow (ϵ), the coloured rings expand outwards in the direction of insertion of the wedge and contract inwards in a direction at right angles to this.

* The drawings of Figs. 32 and 35 were prepared from observations made with a slow "mica step." For all practical purposes the appearances are identical, although the quartz wedge (particularly if it is a steep one) produces a certain amount of distortion of the figure.

Simultaneously the colours are lowered in their order in the two quadrants 2 and 4 in the path of the wedge (where the fast direction of the mineral coincides with slow direction of the wedge) and are raised in quadrants 1 and 3.

In the case of partially developed uniaxial interference figures, *i.e.* where section or grain-face is inclined to the optic axis at any angle up to 90° (when it is parallel thereto), interpretation of the directions image has in most cases to be made on the basis of colour reaction to the compensator, although sometimes a uniaxial mineral will exhibit on complete rotation first a horizontal black band (isogyre), then a vertical band, then a horizontal and finally a vertical band, moving successively into position, rigidly and without curvilinear or sweeping movement across the field; the optic axis in such cases usually lies outside the field of view, but the uniaxial character of the mineral is none the less suggested (*Fig. 33*).

Where the inclination does not reach a maximum and a "quadrant"

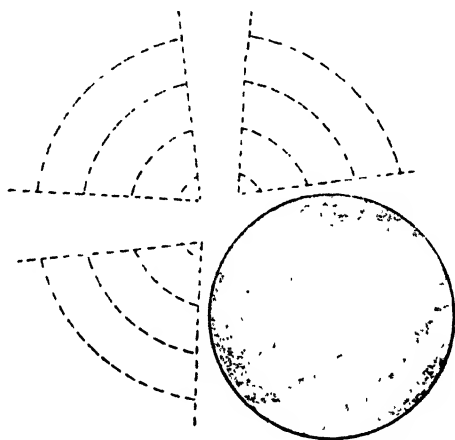


FIG. 33. Partially developed Uniaxial Interference Figure

is discernible, the locus of the optic axis outside the field is not difficult to visualise; the quartz wedge superimposed on this quadrant then has the effect of raising or lowering the colours; in the former case the mineral is positive, in the latter case it is negative. In the extreme case where the section or grain-face is parallel or nearly so to the optic axis, the locus of the optic axis can usually be estimated by appeal to the coloured bands displayed, the highest order colours being nearest to the locus, the lower order colours following successively away from it in the direction of the extraordinary ray e . Determination of slow or fast direction is made in the usual way with a quartz wedge and the sign of the mineral thus obtained.

Biaxial Mineral.—Biaxial minerals have three indices of refraction, α , β and γ ($\alpha < \beta < \gamma$) and, as the adjective implies, two optic axes, which are related as shown in *Fig. 34*. If the bxa coincides with γ (Z),

the mineral is said to be *positive*; if it coincides with α (X), the mineral is *negative* (Z=slow, X=fast vibration directions).

The sign may be determined in one of the following ways:—

- (a) The mineral is *positive*: the isogyres *appear* to move towards each other along the line of insertion of the wedge and the colour-bands move in the directions indicated in Fig. 35 A. The mineral is *negative*: the isogyres *appear* to retreat outwards along the line of insertion of the wedge, i.e. "repel" each other, the colour-bands moving as in Fig. 35 B. This method is, however, somewhat empirical.
- (b) Orientate the figure in the 45° position. The mineral is *positive*: the effect of inserting the quartz wedge (length slow) is to raise the order of the colours due to the mineral within the concave space enclosed by each isogyre and to lower the order of the

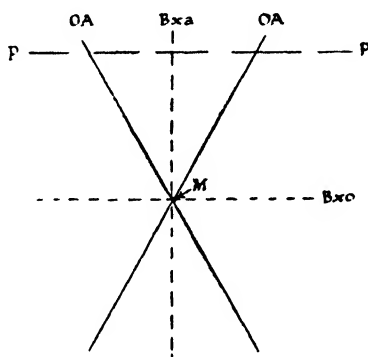


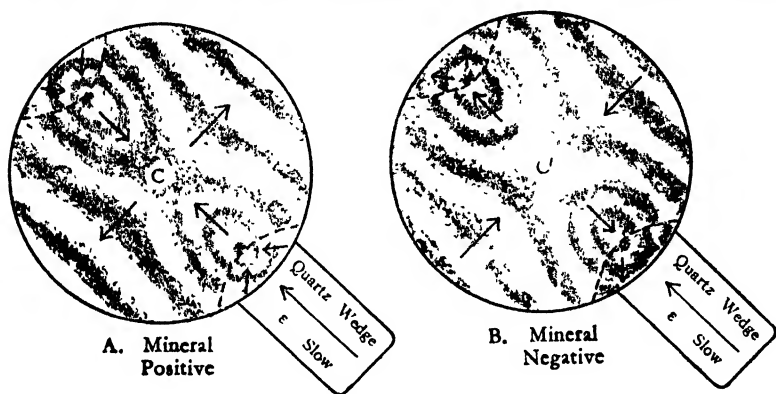
FIG. 34 Diagram of Optic Axial Plane etc.
OA, Optic axis; Bxa, Acute bisectrix; Bxo, Obtuse bisectrix; PP, relative orientation of crystal section which will exhibit a biaxial interference figure; M, Third Mean Line (Optic Normal) at right angles to plane of paper.

colours in the intervening space between the convex sides of the isogyres. The mineral is *negative*: the effect of inserting the quartz wedge as above is just the reverse; lower colours are produced within the concave space enclosed by each isogyre and higher colours in the intervening space between the convex sides of the isogyres. This method is not always conclusive where the isogyres are placed far apart near the boundaries of the field of view or where the colour of the mineral is deep.

- (c) Orientate the figure in the 45° position; the axis of the isogyres is the trace of the obtuse bisectrix (bxo) and its fast or slow vibration character is determined with the quartz wedge in the usual way. The mineral is *positive*: the bxo is fast and corresponds to α or X; the acute bisectrix (bxa) is at right angles to this axis and therefore corresponds to γ or Z. The mineral is *negative*: the bxo is slow and corresponds to γ or Z; the bxa is therefore fast and corresponds to α or X.

Where a mineral section or grain-face is inclined to the acute bisectrix, one isogyre (or part thereof) may be observed which moves across the field as the stage is rotated, becoming most prominent when the 45° position is reached. The convex side of the isogyre then faces the *bxa* and thus the axis of the isogyres is fixed. The fast or slow character of this axis is then measured as described above and thus the sign of the mineral deduced.

Certain minerals, e.g. epidote, exhibit what are sometimes termed "compass-needle" figures, as previously mentioned (p. 172), consisting of one isogyre rotating about a central "point" as the stage is turned; this "point" is, in fact, the emergence of one of the optic axes; such figures constitute special cases where the optic angle approaches 90° . In other cases, depending on magnitude of the optic axial angle, a mineral



The arrows within the field show the directions in which the colour-bands move as the wedge is pushed into the slot.

At C the colours change in *descending* order of Newton's scale until compensation (black) is obtained, after which they change in *ascending* order.

The arrows within the field show the directions in which the colour-bands move as the wedge is pushed into the slot.

At C' the colours change in *ascending* order of Newton's scale.

FIG. 35. Effects of Superimposing Quartz Wedge on Biaxial Interference Figures.

section or grain-face normal to one optic axis may show a straight or curved isogyre according as it is orientated in the 0° or 45° positions. Such characteristics may in themselves be of significance in confirming identity of the mineral.

Finally, any biaxial mineral section or grain-face parallel to the *bxa* or optic axial plane may reveal a figure not unlike that of a uniaxial mineral parallel to its optic axis. In such a case determination of sign depends largely on clarity of the colours and separation of lower from higher order groups if properly developed in opposite parts of the field of view. Where the lower order colours can be correlated with a definite direction, this direction is the *bxa* and a quartz wedge is all that is necessary to determine whether the direction is slow (positive) or fast (negative).

Generally, if some kind of interference figure is revealed, however indifferent in outline or colour value, some useful evidence can be deduced from it, especially by making good use of the quartz wedge and other compensators. Admittedly, detrital minerals often present great difficulties in this respect, not only in cases where the particular grain shows nothing at all (or at least nothing decipherable), but where natural colour, inclusions, superficial staining or alteration products may mask any inherent optical effects. For all practical purposes the information given in this book should suffice, but in special cases where the student is minded to probe this branch of optical physics more deeply, he would be well advised to consult such works as A. Holmes' "Petrographic Methods." (Murby, London), 1921, A. N. Winchell's "Optical Mineralogy." or J. W. Evans' "Determination of Rocks and Minerals."

5(c). *Optic Axial Angle*.—There are various methods of measuring or calculating axial angles where suitably cleaved detrital minerals, crystal fragments or specially prepared sections normal to the acute bisectrix exhibit reasonable biaxial interference figures. A common procedure is to measure or estimate the distance separating the convex sides of opposing isogyres when the crystal is orientated in the 45° position, applicable when the axial angle is not too large. For this purpose a microscope with co-ordinate ruling and fitted into the ocular of the microscope is usually employed. Alternatively, a microscope fitted with a universal stage is employed for more precise measurements of this character.

If the values of the three refractive indices α , β and γ are known, then the optic axial angle can be calculated by the following formula:—

$$\tan^2 V_\gamma = \frac{\frac{1}{\alpha^2} - \frac{1}{\beta^2}}{\frac{1}{\beta^2} - \frac{1}{\gamma^2}}$$

In cases where a mineral presents a face or surface normal to one optic axis, it is possible to estimate the optic axial angle by scrutiny of the amount of curvature of the isogyre. If the latter appears horizontal in the 45° position, the axial angle approximates 90° ; it decreases according as the degree of curvature is observed to increase.

For fuller particulars of such measurements, reference should be made to the works cited below.¹

5(d). *Dispersion of Optic Axes*.—The optic axial angle may be greater or less according as red or violet light is used and this is indicated conventionally by

$$\rho > \nu \text{ or } \rho < \nu$$

There are two general cases:—

- (a) Orthorhombic minerals and those monoclinic minerals in which the optic axial plane includes the b-axis: the hyperbolæ (of the interference figure) show the same amount of dispersion.
- (b) Other biaxial minerals: dispersion may be different for each optic axis.

In the case of (a) assuming $\rho < \nu$ and representing moderate dispersion, a red colour is noted on the concave side of the isogyre and a blue on the convex side; conversely when $\rho > \nu$ with strong dispersion the black isogyres give place to a series of coloured bands.

¹ F. E. Wright, *Carnegie Inst., Washington, Publ.* 158, 1911, p. 147.

A. Johannsen, "Manual of Petrographic Methods," 1914, p. 3.

E. S. Larsen and H. Berman, *U.S. Geol. Surv., Bull.* 848, 1934, p. 22.

In the case of (b), dispersion of each optic axis should be determined separately or alternatively the optic axial angle should be measured, using different coloured light.¹

Diagnosis of Minerals by Refractive Index (Immersion)

Method.—Attention must now be directed to the method of precise refractive index determination as a basis of identification of mineral grains and fragments. The practice has come into prominence considerably during the last two decades, partly due to its popularity with American petrographers and also to the impetus accorded it by E. S. Larsen's work.² The method is invaluable for confirmatory diagnosis of individual mineral particles, but it is obviously unsuited as a means of determining and comparing composite assemblages of heavy minerals for stratigraphical purposes, though this has actually been suggested in some quarters. As W. A. Tarr has said,³ "the predominating factor in the study of sediments in Europe is the use of the microscope"; the tendency in this country is undoubtedly to rely on microscopical analysis, reserving special optical, micro-chemical or spectroscopic tests for doubtful individual cases. On the other hand, these immersion methods could be employed with advantage far more than they are at present, not only as a basis of accurate optical measurements, but in cases of doubtful diagnosis to narrow down possibilities accurately and speedily.

The determinations are most conveniently made by immersing a given mineral fragment or detrital grain in a drop of the selected refractive index liquid on a glass slip and observing their relative relief under the microscope; the application of the Becke Test (p. 166) will indicate whether the mineral possesses a higher or lower refractive index than that of the fluid in which it is immersed. When the refractive indices of the mineral and of the medium are in accord, the former is practically invisible. A glass slip with bowl-shaped hollow, similar to that recommended for mounting coarse material (p. 57) is a convenient form of mount for this purpose.

¹ E. S. Larsen and H. Berman, *op. cit.*

² E. S. Larsen, "The Microscopic Determination of Non-Opaque Minerals." *U.S. Geol. Surv., Bull.* 679, 1921; also with H. Berman, *U.S. Geol. Surv., Bull.* 848, 1934.

³ W. A. Tarr, "Studies of Sediments in European Laboratories." *National Research Council, Researches in Sedimentation in 1924, 1925*, p. 35.

The most satisfactory and commonly applied procedure in determining refractive index of a mineral grain, employing a liquid or other medium of known R.I. as mountant, is that known as the method of oblique illumination, or Schroeder Van der Kolk's method. Comparison is made by observation of the contact between the grain and the medium while part of the field is shaded; this is best achieved by inserting the finger or a piece of card below the stage of the microscope.¹

(i) Using a low power objective and no condenser the results are as follows:—

- (a) Where the grain has a much higher R.I. than the medium, it will present a shadow or dark border towards the side at which the card is introduced and a bright border on the opposite side (*Fig. 36 A*).
- (b) Where the grain has a much lower R.I. than the medium, it will present a shadow or dark border on the opposite side to that at which the card is introduced and a bright border on the other side (*Fig. 36 B*).
- (c) Where the grain has an R.I. approximating that of the medium, the border is observed to be coloured, blue on one side, red on the other. With monochromatic light and transparency, the grain will practically, if not entirely, disappear. The stronger the dispersion of the medium employed, the greater the tendency for the red and blue borders to develop, even when the R.I. of both grain and medium differ only slightly for monochromatic light.

(ii) If a high power objective and the condenser are used, the reaction will depend on the position to which the latter is screwed up. Assuming the focus of the condenser lens to be *above* the grain, then the effects noted in (a), (b) or (c) as

¹ F. Smithson, in a written communication, suggests that, where a slot is provided just above the objective, a glass plate, blackened except for an aperture of about 8 mm. diameter, may be used to produce darkness over half the field. Using this method, a grain of high R.I. gives a dark border towards the dark side of the field.

described will operate. If the focus of the condenser lens is *below* the grain, the effects are reversed.

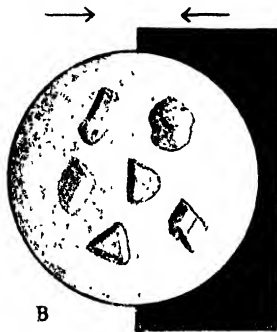
As this method is applicable not only to detrital grains but also to rock minerals in thin section, it should be mastered at the outset of petrographic studies, even though it may take time and practice to accustom the eye to the phenomena. It is a good plan to experiment first with a low power objective, no condenser, mineral grains of known R.I. and a medium (say Canada balsam, cinnamon oil or bromoform) to

Shadow in the
field comes in
from the left.

Card introduced
from the right
below the stage.

Shadow in the
field comes in
from the left.

Card introduced
from the right
below the stage.



R.I. of the grains is higher than that of the medium. Grains are dark on the same side as that on which the card is introduced.

R.I. of the grains is lower than that of the medium. Grains are dark on the side opposite to that from which the card is introduced.

FIG. 36. Immersion Method of R.I. Determination. A. Almandite. B. Fluorite. Both in Clove Oil, R.I. 1.53.

illustrate each of the conditions (a), (b) and (c) above. Thereafter the process should be repeated, using the high power objective and the condenser system to check both possibilities of focal position of the latter. Furthermore, it is advisable to keep at hand mounts, *e.g.* of almandite and fluorite, in Canada balsam for comparison when making this test.

In the matter of actual measurement of the indices, it is obviously the most accurate procedure to measure both ϵ and ω in uniaxial crystals and α , β and γ in biaxial crystals. This necessitates correct orientations of chosen grains, which must therefore be free to move in the medium selected. Further,

observations of birefringence, taking into consideration interference colour-value and thickness as previously described (p. 168), are necessary to assess the lowest and highest indices in terms of optical orientation. It frequently happens, however, that owing to other physical properties, *e.g.* absence of well-defined cleavage or development of fibrous character, it is difficult, if not impossible, to measure all three indices of a biaxial mineral; in such a case every effort should be made to measure β and thus ensure that the value obtained is neither on the low nor high side. In the case of uniaxial minerals, where positive the *lowest* R.I. is ω and where negative the *highest* R.I. is ω ; this can usually be measured in every instance.

Different authors have proposed various liquids as immersion media according to their requirements and taste. It is possible, of course, to establish a very large range of liquids with refractive indices differing by small increments; for those engaged on very close and detailed work, an extended list is given below; generally speaking, however, those liquids marked with an asterisk (*) will suffice for ordinary work; these have the advantage of chemical stability and if carefully looked after will last indefinitely; they are essentially the liquids adaptable for use under field-conditions and are accordingly recommended. It should be noted that R.I. values may vary with temperature; most of those quoted below refer to 20°C. Where an Abbé refractometer is available, the refractive indices of all liquids employed should be periodically checked.

REFRACTIVE INDEX LIQUIDS.

1.333 *Water ¹	1.450 Ethylene Chloride
1.357 *Acetone	1.460 Lavender Oil
1.362 Ethyl Alcohol ²	1.463 Carbon Tetrachloride
1.381 Ethyl Butyrate	1.469 Olive Oil
1.386 Methyl Butyrate	1.470 Russian Alboline
1.393 Ethyl Valerate	1.472 *Turpentine
1.407 *Paraldehyde	1.474 Liquid Paraffin
1.409 Amyl Alcohol ³	1.477 American Alboline
1.425 Ethyl Bromide	1.478 Almond Oil
1.444 *Chloroform	1.481 *Castor Oil
1.448 Kerosene	1.496 Toluol
1.448 Methyl Acetate	1.498 Benzol
1.450 *Petroleum	1.500 *Xylol

1, 2, 3 See notes, p. 183.

1·502	Valvolene ⁴	1·589	Bromoform
1·507	Sandalwood Oil	1·600	*Cassia Oil
1·516	Cedarwood Oil	1·615	Cinnamic Aldehyde
1·516	Ethyl Iodide	1·628	*Carbon Disulphide
1·525	Ethyl Salicylate	1·635	α -Monochloronaphthalene
1·526	Monochlorobenzol	1·655	α -Monobromnaphthalene
1·531	*Clove Oil ⁵	1·700	*Cadmium Borotungstate
1·535	Cinnamon Oil	1·716	Potassium Mercuric Iodide
1·536	Ethylene Bromide	1·737-1·741	*Methylene Iodide ⁶
1·539	Methyl Salicylate	1·778	*Methylene Iodide Sulphur Solution
1·546	*Nitrotoluene	1·868	Methylene Iodide, Sulphur and Iodides ⁷
1·548	Aniseed Oil	1·68-2·10	Piperine and Iodides ⁸
1·550	Bromtoluene	1·998	Na-2·716Li Sulphur and Selenium
1·555	*Nitrobenzol	2·72-3·17	Li Silenium and Arsenic Selenide ¹⁰
1·558	Dimethyl Aniline		
1·561	Monobrombenzol		
1·570	Benzyl Benzoate		
1·572	Orthotoluidene		
1·586	Aniline		

NOTES.

- 1, 2, 3 Solvent action on certain minerals of low R.I.
 - ⁴ Any clean lubricating (mineral) oil may be used; will not mix with clove oil.
 - ⁵ R.I. varies from 1·530 to 1·544; will mix with petroleum.
 - ⁶ Place copper or tin in bottle to prevent discoloration (E. S. Larsen).
 - ⁷ H. E. Merwin, *Washington Acad. Sci. Journ.*, 3, 1913, p. 35.
 - ⁸ H. E. Merwin, *loc. cit.* This and the next two compounds are solid at ordinary temperatures; used in a state of fusion. For preparation, see E. S. Larsen, *op. cit.*, and references cited.
 - ⁹ H. E. Merwin and E. S. Larsen, *Amer. Journ. Sci.*, 34, 1912, p. 47.
 - ¹⁰ E. S. Larsen, *op. cit.*, p. 20.
- N.B.—Solutions of intermediate R.I. can, if required, be obtained by mixing "limiting" fluids together and testing the product with an Abbé or Tully Refractometer, or with mineral fragments of known R.I.

According to E. S. Larsen, about 80 per cent. of known non-opaque minerals falls within the range of R.I. values 1·45 to 1·87. From a purely practical standpoint, the liquids cover this range up to about 1·77, thereafter media solid at ordinary temperatures have to be employed and some of these as "melts" are not too easy to manipulate. Latterly a liquid product known as phenyldi-iodoarsine,¹¹ having an R.I. of 1·743 at 15°C., has been introduced with success and is now generally available.

The best method of storing refractive index liquids is to keep them in "dropping bottles" supplied with a glass rod fused into the stopper. The bottles are kept in receptacles made by boring holes of suitable size in thick wooden blocks, each block containing ten or twelve bottles, on the principle

¹¹ B. W. Anderson and C. J. Payne, *Nature*, 133, 1934, p. 66.

suggested by E. S. Larsen. *Use coloured glass bottles and keep the liquids tightly stoppered in the dark when not in use.*

Summary of Optical Properties of Sedimentary Rock Minerals.—A good working knowledge of crystallography is essential to understanding the several optical properties used in diagnosis of rock minerals, as hitherto described. The following summary of possibilities will help to bring out the basic differences between such properties as may be anticipated from minerals belonging to the various systems of crystallisation and the student would do well to commit the data to memory at an early stage.

1. *Amorphous (Non-crystalline).*—Shapeless grains. No variation in directional properties. *Examples:*—Glauconite, limonite.
2. *Isometric (Cubic) System.*—Grains are singly refracting, isotropic and never pleochroic. *Examples:*—Fluorite, garnet, spinel. Under conditions of internal strain, some species may be anisotropic, e.g. garnet, fluorite.
3. *Hexagonal System.*—Grains are doubly refracting and sometimes pleochroic when coloured. Basal grains or those abraded transverse to the hexad axis are isotropic and yield uniaxial interference figures. Prismatic grains give straight extinction *Example:*—Apatite.
4. *Trigonal System.*—Grains are doubly refracting and frequently pleochroic when coloured. Basal grains or those abraded at right angles to the principal axis are isotropic and yield uniaxial interference figures. Prismatic grains show straight extinction. *Examples:*—Calcite and tourmaline.
5. *Tetragonal System.*—Grains are doubly refracting and sometimes pleochroic when coloured. Basal grains or those abraded transverse to the principal axis are isotropic and yield uniaxial interference figures. Straight extinction for prismatic grains. *Examples:*—Anatase, cassiterite, rutile, xenotime and zircon.
6. *Orthorhombic System.*—Grains are doubly refracting and often pleochroic when coloured. Never completely isotropic. Biaxial interference figures. Prismatic grains show straight extinction. *Examples:*—Andalusite, brookite, enstatite and topaz.
7. *Monoclinic System.*—Grains are doubly refracting, often pleochroic when coloured. Never isotropic. Biaxial interference figure. Straight or oblique extinction according to crystal plane to which surfaces examined are parallel. *Examples:*—Gypsum, orthoclase, epidote and titanite.
8. *Triclinic System.*—Grains are doubly refracting and usually pleochroic when coloured. Never isotropic. Biaxial interference figure. Grains usually give oblique extinction, but often fail to extinguish in any position. *Examples:*—Kyanite and plagioclase feldspar.

N.B.—Exceptionally for grains of biaxial minerals, the crystal-section examined under the microscope may be parallel to the circular section of the indicatrix. Such grains may show very low interference colours or almost isotropism.

Difficulties in Identification of Detrital Mineral Aggregates under the Microscope.—The petrography of sedimentary rocks is frequently complicated by an inherent difficulty of identifying certain rock-fragments, composite grains (compound minerals), iron-, bitumen- or carbon-stained grains, green or white semi-opaque grains of "dirty" appearance and a number of other possibilities well appreciated by those who spend much time in searching mineral concentrates under the microscope. The difficulty is accentuated by fineness of grade when, unless exceedingly good illumination and high power magnification are employed, much of the concentrate may remain obscure; even then, as R. H. Rastall has pointed out,¹ "it is notoriously difficult to apply the ordinary optical tests to very minute grains under a high power, even in the case of transparent minerals, and with opaque grains very little can be done." With a view to aiding diagnosis in such cases, the following hints from the author's experience may not be without some practical value.

Rock-Fragments.—Careful investigation of the coarser constituents of a sediment often reveals large fragments of miscellaneous sedimentary, igneous or metamorphic rocks which may be present as smaller particles in the main mass of the detritus; in this way a clue is obtained and certain types of rock-fragment anticipated. The commonly occurring types range from chert, quartzite, chalcedony, vein-quartz, pegmatite, slate, shale, "felsite," various igneous rocks, particularly the dark-coloured and usually somewhat altered basic hypabyssal and volcanic types, also mica-schist. As pebbles or large particles, these are not very difficult to determine, especially if cleansed of all cementing matter and examined with a strong lens; thin sections are often possible, even on fragments only 5 mm. in diameter. If, however, the coarse constituents reveal no counterpart of the fragments present in the finer mass, much can be done by observing the fragments in reflected light when the colour, form, surface-characters, lustre etc. may suggest identity. Normally, unless rock-fragments possess a high iron-content, they will be segregated by the bromoform-benzol solution or later by bromoform itself in

¹ *Geol. Mag.*, 60, 1923, p. 37.

the process of routine separation previously described so that they should not interfere greatly with the heavy mineral suite.

Composite Aggregates (Compound Grains).—The attachment of iron-ore to quartz, mica to quartz, rutile to ilmenite, pyrite to chert and such compound minerals as leucoxene, perthitic intergrowths of felspar, mica-chlorite aggregates, shimmer aggregates etc. are frequent occurrences in sediments and their diagnosis may occasionally be troublesome.

The compound *iron-ore-quartz* grain should betray its nature by its behaviour with polarised light, when the characteristic concentric interference colours of quartz are normally visible and contrast with the opaque portion identified with reflected light.

Mica-quartz grains are less common, but the two minerals can usually be differentiated by their slight difference of refractive index (mica having the higher value) tested by the Becke line method; the mica portion also will usually show a complete interference figure, while if the concentric coloured rings of quartz are discerned, this property will contrast with the pale grey-blue or grey-yellow colour of the mica; failing this, reflected light will reveal the vitreous lustre of the quartz and the pearly lustre of the mica, usually a sharp contrast.

Compound *ilmenite-rutile* or *ilmenite-anatase* grains are generally straightforward to diagnose, the secondary crystals of the oxides being conspicuous by their colours, refractive indices and euhedrism. Cases have been noted, however, where the co-existence of the ilmenite-rutile aggregate can only be inferred by inspection of the grain by reflected light, when a reddish or crimson patch or border, contrasting with the steel-grey lustre of the unaltered ilmenite, is visible. This characteristic may, however, be noted with certain types of ilmenite in which there is no reason to suspect decomposition and generation of rutile.

Chert as a matrix or nucleus in composite grains is not uncommon, but should be readily identified by its aggregate polarisation; *pyrite* attached to it may be fresh or altered to limonite, in either case recognised by reflected light; pyrite as a core is usually fresh and gives no trouble in identification.

Leucoxene is a much debated substance, but one which is not difficult to label, owing to its characteristic appearance by

incident light; according to A. Cathrein¹ this product is essentially titanite, sometimes accompanied by rutile; it has, however, a very different appearance from titanite and in fact shows every variation from the partially-altered ilmenite grain, through limonite or hematite-stained aggregates to the uniform white "unglazed porcelain" type of grain familiar to all workers.

Perthitic Intergrowths of Felspar are identifiable, providing the grains are not clouded with kaolinitic or micaceous material, when the optical characters are discernible with polarised light; if microcline enters into the composition of such aggregates, the "partial" cross-hatching is always suggestive; if compounded of orthoclase and plagioclase, diagnosis is often difficult, especially with small grains.

"*Chlorite*" aggregates with or without mica are common in certain types of sediment, especially those derived from basic and ultrabasic rocks. Such aggregates are not always easy to decipher, though the bright "ultra blue" polarisation patches of the chloritic minerals contrast with the more vivid coloured mica flakes if these components are individually distinctive; often the aggregate may be a complex product resulting from the decomposition of some aluminous silicate, when the components lose their individuality as definite minerals and reveal themselves in the form of bluish-yellow birefringent grains possessing no particular extinction direction or other property aiding diagnosis; such grains frequently have a curious rough matted surface by reflected light and this feature is sometimes helpful.

Shimmer-Aggregates result from the decomposition of aluminous silicates and usually consist of felted, cryptocrystalline, white micaceous material often crowded with inclusions. These interesting grains are very variable in form and optical character, often possessing no particular directional properties. The interference colours are normally high. By reflected light the felted structure is accentuated and the lustre is that of a semi-vitreous or porcellanous character. G. Barrow has described aggregates of this type with cores of staurolite;² H. H.

¹ *Zeitschr., Kryst. Min.*, 6, 1882, p. 244

² *Quart. Journ. Geol. Soc.*, 49, 1893, p. 349 and Pl. 16, Fig. 5.

Thomas also records their occurrence in the Bunter Pebble Beds of the West of England.¹

Pinite is another aggregate, sometimes mineralogically distinctive, but generally of a micro- to cryptocrystalline character, rather micaceous, green in colour and intimately associated with iron-ore; it usually results from the decomposition of cordierite.

Hematite, either as an isolated mineral or as part of a composite grain, is seldom difficult of recognition on account of its characteristic red colour. If there is any doubt, however, the interposition of a green glass between the source of light and the aggregate (against a grey background) or the use of a green electric lamp may prove helpful; in these circumstances the hematite appears dull black.

Use of Coloured Light in Petrographic Work.—Coloured light as an aid to petrographic work is not perhaps as freely invoked as it might be, either for transmitted or incident light observations. In practically all the instances cited, coloured electric lamps of sufficient strength or the employment of suitable screens made of different coloured glass, may sometimes prove advantageous. The following colours have been successfully employed by the author in this connexion:—

Red for chloritic matter, glauconite, epidote, green mica aggregates.

Green for hematite.

Blue for limonite (especially limonitic patches on glauconite).

Yellow for any aggregate in which either purple ilmenite or pyrolusite is anticipated.

The effect in each case is to make the particular mineral components appear nearly black or quite dull, thus contrasting better with the associated minerals, especially if the latter are transparent or light coloured; such illumination enables the form of the chloritic matter, hematite etc., to be picked out more easily.

Minerals Masked by Alteration Products.—The determination of minerals possessing superficial decomposition products, unremoved by the usual methods of clarification, is a

¹ *Quart. Journ. Geol. Soc.*, 58, 1902, p. 627.

well-known difficulty in work with detrital sediments. The cerium oxide film on monazite, the opaque green-black dust observed as a coating to the commoner pyroxenes and epidote, the chloritic alterations of the ferro-magnesian minerals, the carbonaceous matter associated with andalusite, the various masks assumed by the carbonate minerals: all these are common examples of destabilisation products which serve to hide the true character of the original mineral. Sometimes the product may be diagnosed after careful inspection by incident light, whence the fundamental mineral or existing nucleus may be inferred. The use of the high power objective with convergent light frequently affords sufficient transparency for such deductions to be made with some accuracy; even optical determinations may be possible in these circumstances. On the other hand, the decomposition film is often so thick and comprehensive that the microscope is powerless to resolve it, let alone the primary mineral concerned, in which case experience and intuitive deduction will be the safest guide. In point of fact, it is with these alteration products as with individual detrital grains: often the experienced investigator can be reasonably certain of his diagnosis without being very clear why his conclusions should impress themselves so decidedly on his mind. Perhaps this is one of the psychological peculiarities of this branch of petrographic work, but it is none the less a generally admitted fact.

Against all this and purely as a temporary expedient when comparing mineral assemblages, the labelling of an unknown species as "X," while technically indefensible, may suffice until such time as more extended facilities are at hand for a thorough investigation. The recognition of "X" in a series of samples, providing it has constant mineralogical characteristics, may be of definite index value. While the author in no sense upholds "makeshift" practice, it behoves him none the less to mention at least one way of overcoming a difficulty so that petrographic methods of correlation may proceed without serious interruption arising from ignorance of specific identity.

In cases where every microscopical and other device fails to give a clue to identity, then there is nothing else for it but to hand-pick under the microscope sufficient grains of the un-

known (providing it is not an isolated or rare occurrence) and submit same to chemical analysis or other tests. This often implies treatment of a large quantity of raw material to produce at least 0.5 gm. of the mineral concerned. With isolated grains, the diagnosis of which is essential, spectroscopic methods appear to offer the only solution. (See Chapter VI.)

CHAPTER VIII.

METHODS OF TESTING SEDIMENTARY ROCKS.

Acid Solubility—Bitumen—Treatment of Impregnated Rocks—Matter Insoluble in Carbon Disulphide in Natural Asphalts and Asphaltic Bitumen—Cohesiveness Test of Sands—Density—Frequency Factor—Grain Size—Percentage of Heavy Mineral—Micrometric Analysis—Moisture Content (Hygroscopic) of Sediments—Moisture Content (Hygroscopic) of Impregnated Rocks—Permeability—Porosity—Specific Gravity—Spherulitic Structure—Textural Analysis—Voids—Water Absorption—Weight per Cubic Foot.

IN this chapter, which replaces that entitled “Quantitative Data” in the previous edition of this work, are given detailed descriptions of some of the more important laboratory methods of test now in vogue for determining specific properties and characteristics of sediments. Excluded here are mechanical analysis and optical methods to which Chapters IV and VII respectively are devoted.

A universal desire to introduce the quantitative element more freely into petrographic work finds expression not only in academic spheres of study, but equally in industrial applications where standardisation of raw sedimentary materials or uniformity of definition of certain outstanding characteristics is essential to their utilisation.

Much purely petrographical investigation is perforce qualitative; it depends rather on description than on any degree of mathematical exactitude in defining appropriate characteristics of sedimentary rocks. On the other hand, most rock types are capable of yielding indicative quantitative data enabling more precise comparisons and contrasts to be made and the more this aspect of the science is developed the more thorough is our understanding of the materials involved.

The last few years have witnessed a great advance in methods of testing sediments and mineral aggregates. The essential criteria for a generally acceptable method of test are

that (a) conditions of test, (b) apparatus employed, (c) manipulation, (d) permissible tolerances and (e) interpretation of results, should all be specified so clearly that independent workers on identical samples are in a position to achieve reproducible results. Only on such a basis are comparisons really worth anything.

Petrographic methods as we know them generally, apart from particular national or international standards as to procedure, lack uniformity, also any substantial measure of agreement as to what constitutes the most accurate and unequivocal method of conducting a particular test. This is largely born of multiplicity of independent efforts without any real (and subsequent) co-ordinating plan. Attempts have been made, not without some success, to standardise petrological nomenclature, but the same cannot as yet be said of processes of investigation of sediments and much remains to be done in this connexion. Fortunately industry has given a lead in certain directions and the following descriptions of some of the commoner determinations made with sedimentary rocks will enable the student to introduce a degree of precision and standardisation into the technique of his work.

Acid Solubility.—The acid solubility of a sediment is that proportion which is soluble in hydrochloric acid of a prescribed strength under certain specific conditions. A high acid solubility usually, but not always, implies the presence of organic rocks such as limestone, chalk, ragstone etc. The determination is useful for comparing samples of calcareous rocks from different horizons or localities and for expressing their degree of purity or contamination by the detrital and/or authigenic constituents. The method recommended for sediments is similar to that described in B.S.S. No. 598—1936¹ and is as follows :—

The rock is crushed to pass a 52 mesh B.S. sieve and 5 gm. weighed into a 300 ml. beaker. 25 ml. of 6N hydrochloric acid are added and allowed to stand covered with a watch glass for quarter of an hour or until effervescence has ceased. The addition of a few drops of alcohol to the powder before the acid will accelerate the reaction. 200 ml. of distilled water are then

¹ "Sampling and Examination of Bituminous Road Mixtures."

added, the whole boiled and decanted through a filter paper which has been previously dried and weighed in a weighing bottle. The residue in the beaker is washed twice with cold dilute hydrochloric acid and then several times with hot distilled water and the total contents of the beaker transferred to the filter paper and washed with hot water until the filtrate is free from acid. The residue is dried at $110^{\circ}\text{C}.$ to constant weight and is calculated as a percentage by weight of the original sample taken. The difference between 100 per cent. and the figure is the percentage solubility of the rock. The moisture content (p. 199) need be determined only if there is reason to suspect the presence of an appreciable amount of hygroscopic water. In this case the percentage of moisture would be deducted from the acid solubility as found above.

Bitumen — Treatment of Impregnated Rocks.—Oil-saturated sands containing fluid hydrocarbons may be clarified by repeated digestions of the sample with cold (sometimes warm) benzol, chloroform, ether or carbon disulphide. If, however, the impregnation is of a solid asphaltic character, an extraction process must be carried out. For this purpose it is preferable to take such a quantity of sample (100 gm.) as will give an adequate amount of mineral matter for the preparation of slides of the heavy residue. The method of D. M. Wilson¹ will be found to be a convenient process to use; alternatively, the following, which differs from it only in certain manipulative details, may be employed:—

The sample is reduced by the usual crushing and quartering procedure (p. 27) until two portions approximately 100 gm. in weight are obtained. These are then ground as finely as practicable and dried in the oven for two hours at $105^{\circ}\text{C}.$ It is important to note that samples for precise soluble bitumen determinations should be dry or alternatively the moisture content of the rock should be determined on an aliquot portion of the sample by the method given on p. 199. It will be found that rocks containing low percentages of impregnated bitumen can be ground far more readily than highly impregnated specimens which tend to cake during the grinding process.

Two Whatman No. 5 filter papers, 32 cm. in diameter, are

¹ *Journ. Soc. Chem. Ind.*, 50, 28, 1931, p. 600.

examined for pin holes by holding to the light; if satisfactory they are marked with an identifying number and dried in an oven at 105°C . for two hours, after which they are quickly transferred to weighing bottles and placed in a desiccator. Dry filter papers absorb moisture from the atmosphere extremely

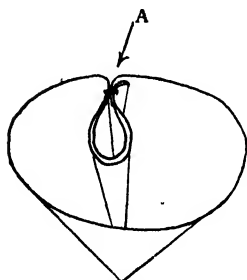


FIG. 37. Method of Folding Filter Paper for Bitumen Extraction.

(After B.S.S. 598—1936, P. 15.)

A. Position of paper clip.

quickly and the transference should therefore be made rapidly. When weighed, the filter papers are folded in the manner shown (*Fig. 37*) and fastened with paper clips, after which they are placed in 8 in. glass funnels, the top edges of which have been ground flat on a carborundum plate.

The weighed sample is carefully introduced into the filter paper and a circular glass plate 9 in. in diameter, with a hole $\frac{3}{8}$ in. in diameter in the centre, placed over the top. The plate is sealed to the funnel, using a cement consisting of:—

Gelatin	...	...	10 gm.
Water	...	...	80 ml.
Glycerin	...	...	20 ml.

One crystal of phenol added to this quantity of cement will prevent the growth of moulds. The cement can easily be re-melted on a water bath and is painted on the funnel rim while hot, care being taken to prevent it running down on the inside of the funnel.

A 3 in. funnel is then placed in the hole in the centre of the plate, with its stem inside the "loop" of the filter paper and trichlorethylene or carbon disulphide added until the level of the solvent is $\frac{1}{4}$ in. below the top of the filter paper. The solvent passing through the filter paper is collected in large bottles and returned to a 5-gallon drum for re-distillation and recovery at a convenient opportunity.

The funnels are re-filled (at intervals) and the level of the solvent kept as high as possible throughout the filtration. On no account should they be allowed to run dry.

When the filtrate is a very pale straw colour (it is never actually colourless within a reasonable period of time), extrac-

tion is considered to be complete and the filter paper is allowed to drain. It is then placed on the top of an oven until most of the solvent has evaporated, after which the paper clip is removed, the paper carefully opened and placed inside the oven. If carbon disulphide has been employed as the solvent the paper should not be placed near a source of heat as long as the odour is very apparent, or it may catch fire. After one hour at 105°C. the paper is removed and the mineral matter scraped from it with the aid of an ordinary nickel spatula and transferred to a previously dried and weighed beaker, which is then returned to the oven and dried to constant weight. The filter paper is also dried for a further hour, after which it is quickly replaced in its original weighing bottle and weighed. The difference between the weight of the original sample and the weight of residue left after extraction gives the amount of soluble bitumen.

If no further examination of the mineral matter is contemplated and the sample is of a fine uniform texture, the soluble bitumen may be determined by the method standardised by the Institute of Petroleum¹; as this particular method requires only 1.5 gm. of rock, the resultant saving of time is considerable. The method is given in full below:—

Matter Insoluble in Carbon Disulphide in Natural Asphalts and Asphaltic Bitumen—I.P.T. Serial Designation—A. 40. — “One to five grams of the natural asphalt or asphaltic bitumen are used for this test.

“The apparatus consists of a glass funnel of approximately 100 mm. diameter, the stem of which is fitted with a tap; the top of the funnel is ground flat. This funnel can be covered with a glass plate which may suitably be of 120 mm. diameter in the centre of which a hole of about 16 mm. diameter has been drilled. Another small funnel is placed so that its stem passes through a cork placed in the hole in the glass plate, the stem being of such a length that its lower end reaches approximately half-way down the tap funnel.

“Two 18.5 cm. No. 5 Whatman filter papers, after being dried in a suitable oven, are cooled in a desiccator, and counterpoised. The papers shall be folded together as illustrated . . .

¹ “Standard Methods for Testing Petroleum and its Products.” 1935, p. 111.

and placed in the tap funnel. A weighed quantity of the asphalt or bitumen is introduced into the filter paper, and the glass plate secured to the funnel by means of gelatine cement in order to ensure that the plate completely closes the funnel, with the object of preventing evaporation of the solvent. This gelatine cement may be prepared by dissolving 10 grams of gelatin in 80 ml. of water and 20 grams of glycerol.

"Carbon disulphide is now added through the small funnel, until the filter paper is about half-filled and allowed to stand for half an hour. The tap is opened and the carbon disulphide, which contains the bitumen in solution, is allowed to run off. The tap is again closed and a further quantity of carbon disulphide introduced through a small funnel into the filter paper. This procedure is repeated until the solvent comes through colourless. A watch glass is placed on the small funnel to minimize evaporation losses.

"When filtration is completed the glass plate shall be removed and the filter papers dried in a suitable (ventilated) oven at about 120°C. (248°F.) for one hour. After cooling in a desiccator, the inner filter paper and its contents are weighed, the outside paper being placed on the weight-pan as a counterpoise.

"The weight represents the weight of the matter insoluble in carbon disulphide, and shall be expressed as a percentage of the original weight of the natural asphalt or asphaltic bitumen taken."

Cohesiveness Test of Sands.—This test is used to determine the relative cohesiveness of different sands and as an indication of the amount of water which will develop optimum cohesiveness (equivalent to "bonding" tests in foundry practice). The simplest method is that known as the "Bar Test," fully described by R. J. Doty¹, and later by H. Ries and C. M. Nevin². It consists in ramming a known quantity of sand in a mould-box with a 20 lb. weight dropped between two guides from a height of 16 in., six blows being given per test. The data required and obtained by this test include the weight of sample in grams, thickness of the bar in inches, average weight of break in grams and recalculated weight of break to one inch

¹ *Foundry*, 51, 1923, p. 15.

² *Trans. Amer. Found. Assoc.*, 31, 1924.

thickness; the correction for water content necessitates knowing the percentage of water with which the sample is gauged and recalculating weight of break to a dry sand basis, on which data all cohesiveness tests should be compared.¹

Density.—The density of a substance is the ratio of its mass to its volume; in other words, it is the mass per unit volume. In the C.G.S. system, it is expressed as grams per millilitre and in the F.P.S. system as pounds per cubic foot. If the temperature at which the determination is carried out is 4°C., the density in C.G.S. units is numerically equal to the specific gravity, which is the mass of a given volume of a substance compared with the mass of an equal volume of water. The mass of a cubic foot of water at 4°C. is 62.4 lb., hence in F.P.S. units the density at 4°C. divided by 62.4 will be equal to the specific gravity of the substance at that temperature. Following the lead given by the British Standards Institution² the use of density at 20°C. in preference to specific gravity at 15.5°C. is now becoming increasingly common in industry.

The general formula connecting density and specific gravity is as follows:—

$$D_t = S.G._t \times d_t$$

where D_t = density of substance at t° .

$S.G._t$ = specific gravity of substance at t° , compared with water at t° .

d_t = density of water at t° .

The methods of determining the density of rocks and incoherent sediments are similar to those employed for specific gravity and are described under the latter heading (p. 209).

Frequency Factor.—The term is applied to the relative proportions of specific minerals or varieties of those minerals occurring in a given heavy residue. There exist various methods of expressing such frequencies, chiefly qualitative and visual. The only satisfactory quantitative method is that of counting grains³ in slides under the microscope; accuracy

¹ See also relevant papers in *Trans. Amer. Found. Assoc.*, 32, 1925.

² B.S.S. 733—1937, "Density Bottles"

³ W. F. Fleet, *Geol. Mag.*, 63, 1926, p. 505; *Proc. Geol. Assoc.*, 38, 1927, p. 1 (cf. p. 449 of this book for application of frequency values to correlation by petrographic methods).

depends as much on completeness of extraction of the total residue from the sample as on actual counting, though it may not be necessary to utilise the whole residue for the count, a system of "proportioning," as with alluvial concentrates, being adopted. Results are expressed as percentages. For details and examples of procedure, see Chapter XI, p. 449; also "Microscopical Measurement of Particle Size," Chapter IV, p. 114.

Grain Size.—Grain size is expressed by the ratio of maximum grain area to mean grain area. With uniform grain-size this ratio is between 1.5 and 2. (See paper by G. H. Gulliver,¹ also A. Holmes.²)

Percentage of Heavy Mineral.—This is expressed as a percentage in terms of original sample :—

$$\frac{100 \times}{w}$$

where x =weight of heavy mineral obtained after separation and w =weight of sample originally taken. The percentage is calculated on the natural rock and not on the acid-cleaned material. In some cases where bromoform of low gravity (2.75) is purposely used to segregate quartz from associated minerals, the percentage of heavy residue >2.9 (bromoform) calculated on the total residue >2.75 is used as a factor in correlation. The same formula applies, but in this case x =net amount of residue >2.9 and w =amount of residue >2.75. Known as the "per cent. H.R. to total H.R. factor," it is an unnecessary refinement if standard bromoform is always employed.

Micrometric Analysis. — In the Delesse-Rosiwal linear method of estimating volume percentages of minerals a celluloid linear or co-ordinate pattern micrometer is employed (stage or eye-piece micrometer) and the size of intercepts for each particular mineral recorded. A number of parallel transverses are examined by moving the slide or micrometer. The total length measured must be from 100-200 times the average diameter of the grains composing the rock. The sum of the intercepts

¹ *Journ. Inst. Metals*, 19, 1918, p. 145.

² "Petrographic Methods" (Murby, London), 1921, p. 341.

recorded for each mineral is reduced to percentage of the sum of individual totals and thus an approximate volume percentage for each mineral established.¹ By the use of S. J. Shand's recording micrometer,² a specially designed stage pattern, much tedious work involved in the former method may be obviated. See also "Microscopical Measurement of Particle Size," Chapter IV, p. 114.

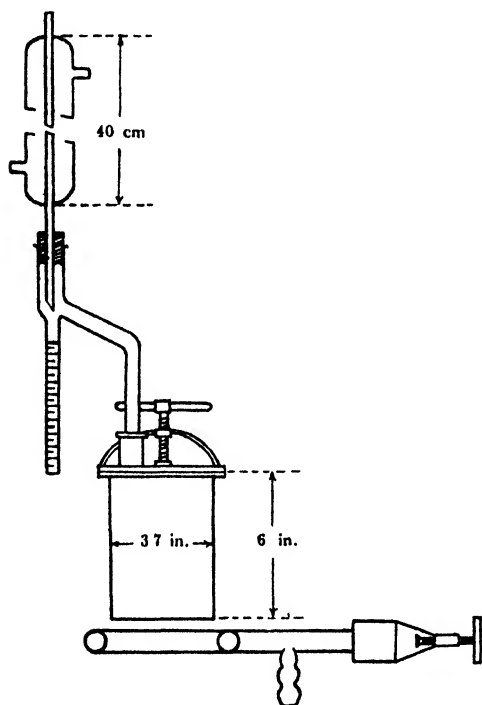


FIG. 38. I.P.T. Moisture. (After B.S.S. 598—1936, p. 24.)

Moisture Content (Hygroscopic) of Sediments. — The general procedure is to place 2 gm. of the rock powder in a squat weighing bottle and dry in an oven at 110°C. for 3 hours, the loss in weight being recorded as hygroscopic water.

Moisture Content (Hygroscopic) of Oil-Impregnated Rocks. — The apparatus used for this determination is shown in Fig. 38 and consists of a copper pot with a flanged top to which the head is attached by means of a clamp, a paper gasket between the two ensuring

a satisfactory joint. A condenser and graduated distilling tube are fitted to the head. A ring burner is employed for heating and, where there is any likelihood of foaming taking place, the heating is commenced from the top. A representative sample of the rock weighing 100 gm. is intro-

¹ A. Holmes, "Petrographic Methods." (Murby, London), 1921, p. 312.

² *Journ. Geol.*, 24, 1916, p. 394; also A. Holmes, *op. cit.*, p. 319.

duced into the pot and 100 ml. of a special diluent added. The latter is petrol free from water and on distillation (I.P.T. G.3) gives 5 per cent. of distillate at a temperature not above 100°C. nor below 90°C., and 90 per cent. at a temperature not above 205°C. The lid is then clamped in position and heat applied to the pot, distillation being continued until no further water collects in the tube. The volume of the latter is then noted and the percentage of water in the sample calculated.

Permeability.—The permeability of a porous substance is the volume of fluid of unit viscosity which passes through unit cross-sectional area in unit time under a unit pressure gradient. There is no direct connexion between porosity and permeability, although it is true that highly porous rocks are usually very permeable. This is, however, only because the pores are interconnected and it is obviously theoretically possible for a rock to have a large number of closed pores without being permeable. The porosity of a number of spheres of equal diameter is independent of their size, but their permeability depends on the size of the interstitial openings. Under certain special conditions, the approximate value of the permeability may be calculated from sieve analyses and porosity determinations, but in most cases it is preferable to make a direct determination. Full details of the method employed for oil-well samples will be found in a paper by R. D. Wychoff, H. G. Botset, M. Muskat and R. D. Reed.¹ These consist essentially in forcing a liquid or gas through a sample of known dimensions sealed in a brass tube and measuring the rate of flow of the fluid and the pressure gradient. Where a liquid is employed, the permeability is given by :—

$$K = \frac{\mu QL}{A(P_1 - P_2)}$$

where K = permeability.

μ = viscosity of liquid.

A = cross-sectional area of the core.

L = length of core.

$P_1 - P_2$ = difference of pressure at in-put and out-put ends.

Q = volume of liquid passing in unit time.

With a gas, the rate of flow is proportional to the difference in the squares of the pressure at the in-put and out-put

¹ *Bull. Amer. Assoc. of Petrol. Geol.*, 18, 1934, p. 161.

ends, but the formula for the permeability reduces to one identical with that for liquids, except that Q now refers to the flow corresponding to the algebraic mean pressure in the flow channel.

The sample used for permeability measurements is a core, about 5 cm. in diameter and 1 cm. in length, which is cut from the rock (either parallel or transverse to the bedding plane) with a slotted brass tube fed with carborundum. The ends of the cores are "trued" and precautions are taken during this operation to avoid "clogging" the surface pores. The core is then dried and the oil if present removed by extraction in a Soxhlet apparatus, after which it is sealed in a brass tube with hot pitch or sealing wax.

When liquids are used for permeability measurements the core is mounted vertically with the inlet end facing downwards, so that the top surface is always kept covered with liquid and capillary forces thereby eliminated. The danger of trapping air in the pores is avoided by admitting the liquid under vacuo. Precautions are necessary to avoid "plugging" the pores of the core through the use of water containing dissolved silicic acid or oil containing gummy substances. Such devices as filtering water through an alundum filter or storing oil in nitrogen after removing unsaturated bodies are quite satisfactory. A further difficulty is sometimes encountered if the matrix cementing the grains together dissolves in the liquid used for making the permeability measurement, in which case the pores become "stopped" by the detached grains. For such samples, organic liquids such as carbon tetrachloride are most convenient. With liquids at constant temperature, the rate of flow plotted against the pressure difference should give a straight line.

In addition to the precautions noted above, the core must be very carefully dried, preferably in a vacuum, to eliminate all traces of moisture when gases are employed for permeability measurements. To preserve this condition throughout the test, the gas employed must also be dried. While it is sufficient with liquids to measure differences of pressures, for gases, both the in-put and out-put pressure must be determined, as the rate of flow is proportional to the difference in the squares of these pressures. The rate of flow of the gas is measured by a water

displacement method or by a meter if a high rate of flow is employed. Observations are made at several pressures and the rate of flow at the mean pressure plotted against the difference in the absolute pressures, when the result should be a straight line. The values for permeability obtained by gas measurements are in agreement with those obtained using liquids, but the advantages of using gases are that (1) the danger of "clogging" the pores or disintegration of the sample is altogether eliminated; (2) errors due to entrapped air are avoided; (3)

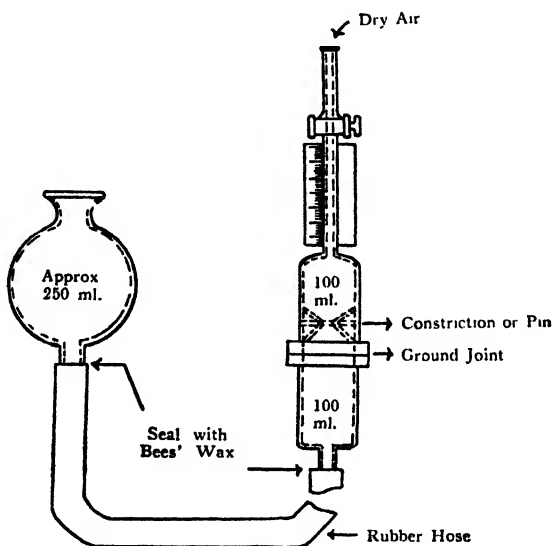


FIG. 39. McLeod Porosimeter.
(After A.S.T.M. Standards, 1933. Part II Non-Metallic Materials, p. 1084.)

assuming air is employed, there is no necessity for evacuation and (4) the use of excessive pressures is avoided.

Further details on the measurement of permeability will be found in a paper by H. J. Fraser,¹ who describes porosity and permeability experiments with collections of individual spheres and discusses the effect of particle size, shape, degree of compaction and various other factors on the permeability of sediments.

¹ "Experimental Study of the Porosity and Permeability of Clastic Sediments." *Journ. Geol.*, 43, 1935, p. 910.

Porosity.—The porosity of a rock is the volume of the pores or air spaces it contains expressed as a percentage of the total volume of the sample.

$$\text{Porosity} = \frac{\text{Volume of pores} \times 100}{\text{Volume of rock substance} + \text{volume of pores}}$$

Methods by which porosities are determined fall into three main classes.

- (i) Direct methods for more or less compact rocks.
- (ii) Indirect methods for more or less compact rocks.
- (iii) Methods for loose sediments, sands, grits etc.

(i) *Direct Methods for Compact Rocks.* — The volume of open pores in a rock may be determined directly by a porosimeter, such as that shown in *Fig. 39*, which is the apparatus prescribed by the American Society for Testing Materials for the testing of electrical porcelain.¹ This consists of a cylindrical receptacle for the sample, having the top edge ground flat and connected at the bottom with a mercury reservoir. A cap fits over the top and attached to it is a capillary tube and scale for measuring the volume of air withdrawn from the sample. A constriction in the cap prevents the specimen from rising. For rocks with up to 1 per cent. porosity, the effective volume of the capillary should be approximately 0.5 ml. More porous rocks require a longer or wider capillary. The edge of the specimen should be freshly fractured and two or more pieces with a total volume about 50 ml. placed in the receptacle. The ground glass joint and stop-cock are then greased and made air-tight. Moisture is removed from the inside of the apparatus and from the specimen by completely filling the interior with mercury, closing the stop-cock and then lowering the reservoir so as to create a vacuum. This is maintained for 1 minute and the reservoir then raised and the gas collected in the capillary tube expelled. The levelling bulb is now lowered and the specimen exposed to air for 1 minute, after which the level of the mercury is again raised above the stop-cock and the latter turned. The reservoir is now re-lowered, a vacuum maintained for at least 1 minute and the volume of expelled air measured by raising the

¹ A.S.T.M. D 116—30.

reservoir until the levels of the mercury in the reservoir and capillary are the same. With this particular type of porosimeter the total volume of the sample must be determined by some other means, such as weighing in water (p. 208).

(ii) *Indirect Methods for Compact Rocks.* — The commonest method of determining porosity is by calculation from the true specific gravity of the rock substance (*i.e.* the powdered rock) and the specific gravity of the rock in bulk. The latter is here called "apparent specific gravity," but it should be noted that the term has other meanings as, for example, a specific gravity to which the correction reducing the weights to a vacuum has not been applied.

The relationship between the porosity and the specific gravity of the rock in bulk and powder form is as follows :—

Let P_1 = Porosity of the rock,

G_1 = True specific gravity (C.G.S. units),

G_2 = Apparent specific gravity of the rock in bulk (C.G.S. units),

d = density of water at the temperature of test.

Then 1 ml. of rock in bulk weighs $G_2 d$.

But this contains $(1 - \frac{P_1}{100})$ ml. of rock substance, which will weigh :—

$$dG_1(1 - \frac{P_1}{100})$$

$$\text{whence } G_2 = G_1(1 - \frac{P_1}{100})$$

or

$$P_1 = \frac{100 (G_1 - G_2)}{G_1}$$

The apparent specific gravity is usually determined on pieces of rock about 2-3 in. in diameter, which for precise work should be reserved and later dried and crushed to a powder for the determination of true specific gravity. It is essential that the sample should be large enough to be representative and the larger the pores in the rock the bigger must be the sample.

The piece of rock is first dried to constant weight at 100°C., a process which may take as long as 3 days. It is then weighed and placed in a vacuum desiccator of the type shown in *Fig. 40*. The pressure is reduced to 1 mm. and distilled water, which has previously been boiled and cooled, admitted through the tap funnel until the specimen is completely covered. The latter is left overnight and in the morning is suspended by a thin wire in water and weighed, a correction being applied for the weight of the wire in water. It is then removed and surface dried by wiping with a cloth and rapidly weighed.

If W_1 = Weight of dried piece of rock,
 W_2 = Weight of rock in water,
 W_3 = Weight of surface-dried rock,
 G_2 = Apparent specific gravity,

$$\text{then } G_2 = \frac{W_1}{W_3 - W_2}$$

This method is not recommended where large pores are present, *e.g.* coke, and in such cases it is advisable to use a wax coating method (p. 206).

In the absence of closed pores, the specific gravity (G_3), calculated from the formula

$$G_3 = \frac{W_1}{W_1 - W_2}$$

should be the same as the specific gravity of the powdered rock (G_1). If closed pores are present, the specific gravity of the powdered rock will be the higher of the two and the percentage of closed pores (P_2) will be given by

$$P_2 = \frac{100 (G_1 - G_3)}{G_1}$$

A vacuum desiccator is not essential in porosity determinations, but it enables a determination of closed pores to be made. If only the apparent specific gravity of the rock is required, it is sufficient to place a piece in water for 24 hours and then weigh it in water and surface-dry it. The apparent specific gravity may then be calculated from the formula given

on p. 204. Before crushing to a powder to ascertain the true specific gravity, the rock must again be dried to constant weight.

An alternative method of determining the apparent specific gravity is to apply a wax coating to the dried and weighed sample. In this case a layer of molten wax about 1/10th in. thick is brushed over the surface of the rock, which is then re-weighed, suspended in water and again weighed.

If W_1 = Weight of dry rock,
 W_2 = Weight of dry rock + wax,
 W_3 = Weight of dry rock + wax in water,
 S = Specific gravity of wax,

$$\text{then volume of wax} = \frac{W_2 - W_1}{S}$$

$$\text{and specific gravity of rock} = \frac{W_1}{W_1 - W_3 - \frac{(W_2 - W_1)}{S}}$$

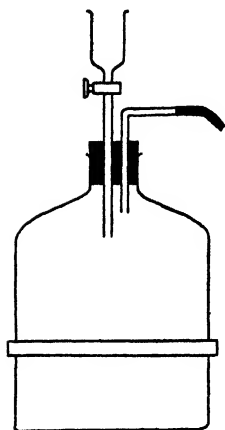


FIG. 40. Vacuum Desiccator.

For the true specific gravity determination, the rock is dried to constant weight and crushed to such a state of division that pores are eliminated. For most purposes a powder completely passing a 100 B.S. sieve is suitable. A clean, dried and weighed specific gravity bottle is two-thirds filled with the powder and re-weighed, after which it is placed in a vacuum desiccator carrying a tap funnel, as shown in Fig. 40. The desiccator is evacuated to 1 mm. pressure and distilled water, which has previously been boiled and cooled, added slowly through the tap funnel until the bottle is full, when the pressure is slowly in-

creased to atmospheric. If the level of the water in the neck of the bottle is carefully watched during the latter process, it is easy to see whether any air bubbles are present as they will cause the level to fall when air is admitted to the desiccator. If bubbles are absent the bottle is removed, placed in a bath of

water at 15.5°C. and allowed to remain there for 30 minutes, at the end of which time the stopper is inserted and the bottle wiped and re-weighed.

If W_1 = Weight of bottle full of distilled water at 15.5°C. ,
 w = Weight of bottle,
 W_2 = Weight of bottle + rock,
 W_3 = Weight of bottle + rock + water to fill bottle at 15.5°C. ,
 then

$$G_{15.5}^{\text{rock}} = G_1 = \frac{W_2 - w}{(W_1 - w) - (W_3 - W_2)}$$

Where a suitable vacuum pump is not available, wetting will, in general, be more easily achieved with an organic liquid such as kerosene, toluene or carbon tetrachloride than with water. The greater volatility and coefficient of expansion of organic liquids necessitate more care in carrying out the determination, especially in hot weather, but losses due to evaporation may be minimised if after immersing the bottle for 30 minutes in a water bath at 15.5°C. the stopper is inserted and quickly wiped and the bottle transferred to a bath of very cold water until a bubble of air forms in the neck of bottle. This gives ample time to complete drying and weighing the bottle before the solvent emerges from the stopper. Where a liquid other than water is employed, the specific gravity of the rock is given by

$$G_1 = \frac{(W_2 - w) \times G_4}{(W_1 - w) - (W_3 - W_2)}$$

where G_4 = specific gravity of liquid at 15.5°C. compared with water at the same temperature,
 and the remaining symbols have the same meaning as before.

A convenient procedure where the determination is to be carried out at normal pressure is to weigh the specific gravity bottle and fill it to about quarter of its capacity with the liquid to be employed. The powdered rock is weighed out on a watch

glass and transferred with a camel-hair brush to the bottle by a small glass or metal funnel with a very short stem. More liquid is added when the powder rises above the surface. After all the powder has been added, the bottle is nearly filled with liquid and well shaken, after which the determination is completed in the normal manner. By adding the rock powder to the liquid instead of *vice versa* it will be easier to eliminate air bubbles.

(iii) *Methods for Loose Sediments etc.* — In general the methods adopted for loose sediments consist in filling a suitable container of known volume by some standard procedure which enables the same degree of compaction to be easily reproduced and then either calculating pore space from the specific gravity of the material or measuring the quantity of water required to fill the interstices between the grains. The apparatus commonly used for the latter purpose consists of a hollow metal cone of capacity 1/10 cu. ft., which is connected at the base with a measuring cylinder by means of a piece of rubber tubing and a clip. The measuring cylinder is filled with water to the top mark and the clip opened. Water is allowed to enter the cone until it appears above the level of the sand and the volume so admitted, expressed as a percentage of the volume of the cone, gives the porosity or void content of the sediment. The results obtained by such methods are not always trustworthy, as not only is it difficult to devise a method of filling which will always give a reproducible degree of compaction, but also the interstices of the sand grains are usually not completely filled with water unless the latter is admitted under a vacuum. It is preferable, therefore, to determine the void or porosity content of sediments by calculation from the weight of a known volume compacted under carefully standardised conditions. F. H. King¹ employs for this purpose a cylindrical metal or glass container, internal diameter 5.8 cm., internal height 3.5 cm., with a circular glass lid 6.3 cm. in diameter, ground on one side. The volume of the container is first found by filling it with distilled water and sliding on the glass lid, so that no air bubbles are present, after which it is dried and weighed. The container is emptied and dried and the sample admitted in a

¹ *U.S. Geol. Surv., 19th Ann. Rep., 2, 1897-8, p. 207.*

fine stream either from a small funnel or by other suitable means. During this process the container is slightly tilted and gradually rotated and at the same time its bottom edge lightly tapped on the bench. It is slightly overfilled and the excess removed by sliding the glass plate gently across the top of the jar. The method gives the maximum degree of compaction corresponding with the minimum void content. Further tapping should not result in any diminution in volume.

If w = Weight of water to fill the container,

W = Weight of sand to fill the container,

s = Specific gravity of sand,

then the porosity or void content

$$= \frac{w - \frac{W}{s}}{w} \times 100$$

and weight per cu. ft. (consolidated)

$$= \frac{62.4}{w} \frac{W}{s} \text{ lb.}$$

Methods suitable for mineral aggregates, sands and fillers are described in B.S.S. No. 812—1938. These follow the general principle given above in that for each type of material the procedure is to calculate the porosity (or as it is often called, the void content) from the volume weight of the material (p. 212) and its specific gravity (or density).

Specific Gravity.—Methods suitable for determination of specific gravity may be classified as follows:—

(a) Hydrostatic method of weighing in water. See p. 203 under “porosity,” for detailed description. The method is not generally used for incoherent sediments but is suitable for compact rocks.

(b) Displacement method. This is commonly employed for incoherent sediments. A suitable flask for this determination is the Le Chatelier type with a graduated neck as described in B.S.S. No. 598—1936 “Sampling and Examination of Bituminous Road Mixtures.” The flask is filled with kerosene to

one of the marks below the bulb in the neck, after which it is immersed in water at 20°C. for half an hour. Approximately 50 gm. of the dried material are accurately weighed and slowly introduced into the flask, due precautions being taken to prevent the material adhering to the neck above the level of the kerosene. Air-bubbles are eliminated by gently tapping

the flask on a pad. The flask is then replaced in the water bath and after half an hour the level of the liquid is observed. The difference between the two readings gives the volume of the sample and enables the density at 20°C. to be easily calculated. The density of a sediment at 20°C. differs from its specific gravity (also compared with water at 20°C.) by about three parts in a thousand, but as this is also approximately the limit of accuracy of the method it is not usual to apply any correction when specific gravity is required.

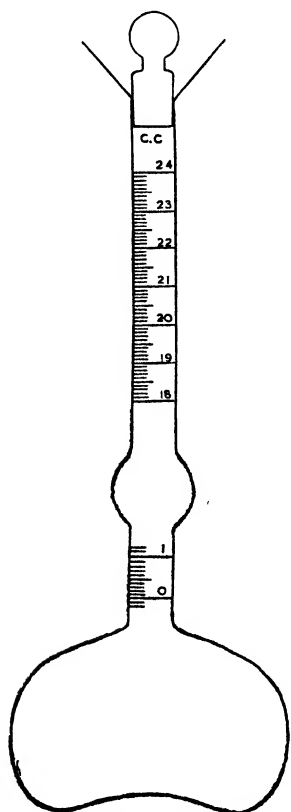


FIG. 41. Le Chatelier Flask.

(c) Jolly spring balance method. This is an approximate method suitable for small specimens. First of all a reading "a" of the bead pointer is taken. The specimen is then placed in the upper pan and a new reading taken "b." The specimen is then transferred to the lower pan in water, the height of the beaker adjusted and a third reading taken "c." Then $b-a$ is proportional to the weight of the specimen in air and $b-c$ to its loss in weight in water, whence

$$\text{Specific gravity} = \frac{b-a}{b-c}$$

(d) Specific gravity bottle method, for sands and inco-

herent sediments. See p. 203 under "Porosity," for complete description of procedure.

(e) Sollas diffusion column (methylene iodide method) for isolated mineral fragments. Use a test-tube and pour in about 2 ml. methylene iodide and then (carefully) 10 ml. benzol. Allow the tube to stand (corked) until diffusion has taken place, usually about 24 hours. Then insert a fragment of the mineral M, the S.G. of which is required and two fragments of substances A and B, the known S.Gs. of which are respectively $>$ and $<$ M (found by trial from selection of previously tested fragments). A scale should be clamped behind the tube so that the distances of M from B and A are comparable.

Then if b = S.G. of B, a = S.G. of A and m = S.G. of M,

$$\frac{a-m}{m-b} = \frac{AM}{BM}$$

where AM is distance of M from A and

BM is distance of M from B.

$$\text{Whence } m = \frac{bAM + aBM}{AB}$$

(f) Other methods for the determination of specific gravity are the Walker Steel-Yard Balance (for large specimens) and the Westphal Balance (chiefly for liquids). These are described fully by A. Holmes¹ and H. Miers.²

Spherulitic Structure.—Study of the form of surface of contact between two interfering spherulites may throw light on the law of their growth. This matter has been discussed by B. Popoff³ and A. Harker.⁴ E. Spencer⁵ has also discussed the relevant mathematics in an appendix to his paper on spherulitic siderite.

¹ "Petrographic Methods and Calculations." (Murby, London), 1921, chapter II.

² "Mineralogy," 2nd ed. (Macmillan, London), 1929, p. 211.

³ *Förh. Nord. Naturf. Helsingfors*, 1902, sect. IV; *Tscherm. Min. Petr. Mitth.* (2), 23, 1904, p. 153.

⁴ "The Natural History of Igneous Rocks." (Methuen, London), 1909.

⁵ *Quart. Journ. Geol. Soc.*, 81, 1925, p. 693; also references on p. 692.

Textural Analysis.—This concerns the quantitative expression of texture of sedimentary rocks in terms of grade-sizes and shapes of clastic constituents. It is applied particularly to sands, sandstones, grits, conglomerates, breccias etc. Grade-size is expressed conventionally as summarised under "Mechanical Analysis" (p. 85), while shape is expressed quantitatively by C. K. Wentworth's method (p. 118), or suitable alternative, or more usually qualitatively as rounded, sub-angular or angular. Other determinations under this heading are percentage heavy mineral per grade-size, percentage of one or more characteristic shapes of constituents developed and measurements of any particularly prominent structures observed in the rock under analysis.

Voids.—See porosity of loose sediments, p. 208.

Volume Weight (or Weight per Cubic Foot). — The methods given below are suitable for incoherent materials and are described in full in B.S.S. 812—1938.¹

(A) *Method for Coarse Aggregates.*—The sample, if moist, is spread out and allowed to dry under room conditions, after which it is thoroughly mixed. A tared cylindrical metal vessel (capacity 1 cu. ft. where largest particles exceed $1\frac{1}{2}$ in. or $\frac{1}{2}$ cu. ft. where largest particles are from $\frac{1}{2}$ – $1\frac{1}{2}$ in. size) is then filled to one-third of its capacity and tamped 25 times with a steel rod 24 in. long and $\frac{5}{8}$ in. diameter, having a bullet-nosed point. The strokes of the tamping rod are distributed uniformly over the surface of the aggregate and the rod is not allowed to touch the bottom of the container. The container is next filled two-thirds full and the tamping repeated, using only sufficient force to penetrate the last layer. Finally, the container is filled to overflowing, again tamped 25 times, the surplus aggregate removed, using the tamping rod as a straight edge, and weighed. The exact capacity of the container in cu. ft. is found by weighing it full of water at 20°C. and dividing this weight in lb. by 62.4.

(B) *Method for Fine Aggregates.*—The weight per cu. ft. of fine aggregates such as sands may be determined in a similar manner using a $1/10$ th cu. ft. container (6 in. in diameter and 6 in. in height).

¹ "Sampling and Testing of Mineral Aggregates, Sands and Fillers."

(C) *Method for Fillers.*—The sample is dried and, after cooling to room temperature, is poured into a weighed 100 ml. B.S. graduated glass measuring cylinder, having an internal diameter between 1 in. and $1\frac{1}{4}$ in., to approximately the 100 ml. mark. The cylinder and contents are then weighed and after inserting a stopper are subjected to a series of taps by dropping repeatedly from a height of approximately $\frac{1}{2}$ in. on to a non-resilient surface. Tapping is continued until no further diminution occurs in the volume occupied by the filler.

$$\text{Volume weight} = \frac{\text{Weight of filler in gm.}}{\text{Minimum volume of filler in ml.}}$$

Water Absorption.—The water absorption of a rock is the percentage by weight of water absorbed under certain prescribed conditions. Among other factors it is influenced by the size of sample, the time of immersion and temperature of water during immersion; for this reason conditions under which the test is being carried out should always be stated. In some laboratories it is the practice to immerse the dry rock in water for 24 hours, in others for 3 days. The water may or may not be raised to the boiling point and the size of sample may vary from about 50 gm. to several kgm. As a rule not more than half of the total pores in rocks used for road purposes can be filled by simple immersion, even though this be prolonged for several days. At the outset the water enters comparatively rapidly, but thereafter the rate soon diminishes.

The method adopted by the British Standards Institution for determining the water absorption of stone to be used in road carpets is as follows:—

B.S.S. 594—1935, p. 29. *Appendix E. Method of Testing Stone for Absorption of Water.*—“At least three roughly cubical samples of the stone to be tested shall be selected of approximately 50 grammes each in weight; sharp edges shall be filed down and the samples carefully brushed to remove any loose fragments.

“The samples shall then be placed in an ordinary air-oven fitted with a thermometer and maintained at a temperature of from 100°C. to 110°C. for at least 72 hours. The samples shall then be taken out of the oven, allowed to cool down in a

desiccator and *immediately* weighed to obtain their dry weight (W).¹

"The samples shall then be placed in a suitable trough and distilled water allowed to creep over them until they are completely immersed in about 4 hours, and they shall be left thus immersed for at least 72 hours to ensure maximum saturation.

"Each sample shall then be taken out of the trough, and, after first removing loose surface moisture with an absorbent cloth (a piece of smooth linen towel is very suitable), weighed *immediately* to obtain its saturated weight in air (S).

"The amount of absorption expressed as a percentage of the dry weight is then obtained from the formula :

$$\text{Absorption} = \frac{S - W}{W} \times 100."$$

A slightly different procedure is generally followed where the rock is in the form of an aggregate intended for use in concrete. A representative sample weighing above 3,000 gm. for aggregates containing pieces up to 1½ in. in size is well washed and dried to constant weight. It is then immersed in water for 24 hours and at the end of this period the water is poured off and the aggregate dried by wiping with an absorbent towel and immediately weighed. In order to minimise the error due to loss by evaporation, it is advisable to have two operators to carry out the latter operation. The aggregate (surface dry) is then placed in an oven at 100°C. and again dried to constant weight. The water absorption of the aggregate is the difference between the surface dried weight and the final weight expressed as a percentage of the final weight.

Weight per Cubic Foot.—See "Volume Weight," p. 212.

¹ A physical balance to weigh 100 grm. in each pan and sensitive to 5 milligrammes is sufficiently accurate."

CHAPTER IX.

DIAGNOSTIC PROPERTIES OF SEDIMENTARY ROCK MINERALS.

IN this chapter is a summary of the principal properties of mineral species likely to be found in sedimentary rocks. Excluding purely alluvial minerals and those essentially recent products of local environments, the data will be found complete for all normal work as far as present knowledge goes. Obviously, of a total of some eight thousand different minerals now known to science, a very large percentage is capable of occurring in sedimentary deposits, given relevant parent-rocks in the region concerned; exhaustive treatment would thus demand an unwieldy treatise on detrital mineralogy which every consideration renders impracticable. Experience, however, shows that a comparatively small proportion of minerals is identifiable in sedimentary rocks of *any geological age* and that it is only when recent, especially alluvial, deposits are studied that the list can be indefinitely expanded; even in the latter case, it is in some respects surprising how many species fail to survive and study of the records of alluvial minerals from all over the world soon reveals the restriction of species imposed by rapidly destructive chemical and mechanical forces.¹

The detailed information given in this chapter should in itself be sufficient for determining a particular mineral, but a working knowledge of crystallography—a *sine qua non* to this particular study—is assumed throughout. As will be seen, the information is arranged under stereotyped headings, *viz.* chemical composition, system of crystallisation, habit, structure, cleavage, fracture, hardness, specific gravity, lustre, colour, magnetic and electrostatic properties, optical properties, characters in sediments, occurrence, possible sources of deriva-

¹ C. Raeburn and H. B. Milner, "Alluvial Prospecting." (Murby, London), 1927, p. 324.

tion, remarks and special references to recorded occurrences or to general literature.

Chemical Composition.—Minerals vary widely in composition, especially the more complex silicates. Except in simple cases formulæ given are empirical and designed to indicate elements normally concerned in the composition of the species rather than precise chemical constitution. In a majority of cases the formulæ quoted are those cited by E. S. Larsen and H. Berman.¹

System of Crystallisation. — With few exceptions, *e.g.* pseudohexagonal forms in the orthorhombic system and certain doubtful monoclinic and triclinic species indicated with a (?), the crystal systems quoted are definite.

Habit.—Under this heading is given in order of occurrence the common form of the crystallised mineral which may be expected, *ceteris paribus*, to determine the average appearance of the detrital grain. The notation of the crystal faces to be anticipated is given, while twinning, if any, is conventionally defined. It should be remarked in the latter connexion that, while many minerals are prone to exhibit twinning in their native environment, such developments, save for example the felspar group, seldom seem to persist in sediments.

Structure.—This has reference to the tendency of the native mineral to occur either as crystalline or in particularly characteristic forms. The former may be expected to predominate in sediments.

Cleavage.—The principal directions of cleavage are quoted in order of perfection. The property is a very important one with detrital minerals, in that in a majority of cases it tends to determine the relevant crystal face presented by the sedimentary rock species. Parting planes are also quoted under this heading.

Fracture.—This again has reference to the mineral in its native state and from the standpoint of its detrital derivative is a guide to what must be anticipated as regards shape.

Hardness.—The values quoted are in accordance with Mohs' scale. (See Appendix III, p. 605.)

¹ "The Microscopical Determination of the Non-Opaque Minerals." 2nd ed. U.S. Geol. Surv., Bull. 848, 1934.

ISOMETRIC SYSTEM

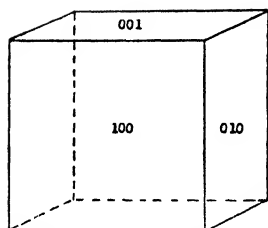


FIG. 42. Cube (a).
e.g. Thorianite.

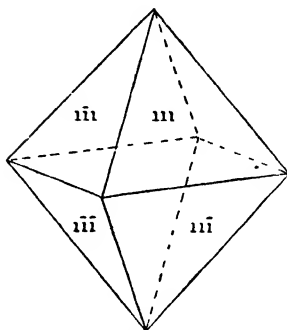


FIG. 43. Octahedron (o).
e.g. Gold, Magnetite, Spinel.

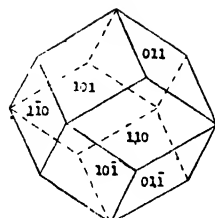


FIG. 44. Dodecahedron (d).
e.g. Gold, Garnet.

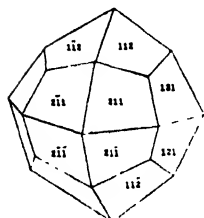


FIG. 45. Trapezohe-
dron or Icositetrahe-
dron (n).
e.g. Garnet.

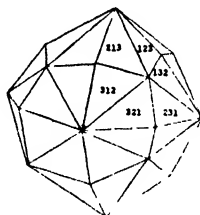


FIG. 46. Hexoctahe-
dron (s).
e.g. Diamond.

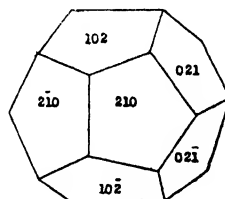


FIG. 47. Pyritohedron (e).
e.g. Pyrite.

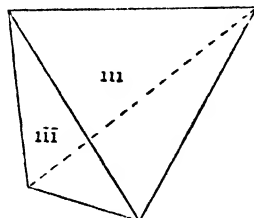


FIG. 48. Tetrahedron (o).

NOTE.—FIGS. 42-77 taken from C. Raeburn and H. B. Milner, "Alluvial Prospecting" (Murby, London), 1927, p. 328-333.

TETRAGONAL SYSTEM

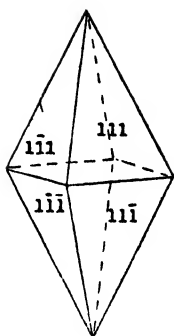


FIG. 49. Pyramid
(p).
(First Order.)
e.g. Anatase.

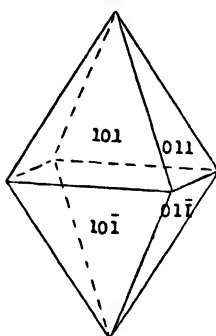


FIG. 50. Pyramid (e).
(Second Order.)

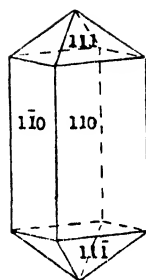


FIG. 51. Prism
(m) & Pyramid
(p).
(First Order.)
e.g. Zircon.

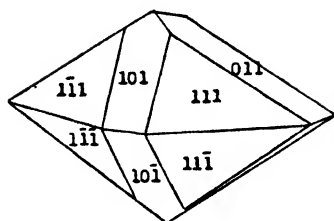


FIG. 52. Pyramids (p) and (e).
(First and Second Order.)
e.g. Cassiterite.
(After Dana.)

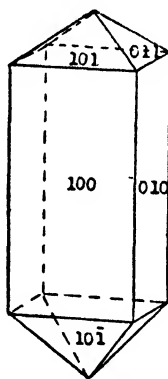


FIG. 53. Prism (a)
and Pyramid (e).
(Second Order.)
*e.g. Zircon (in com-
bination with other
forms).*

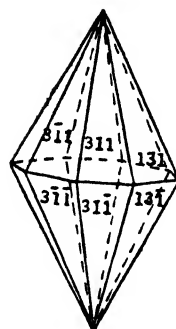


FIG. 54. Ditetra-
gonal Pyramid (x).
*e.g. Zircon (in com-
bination with other
forms; not found
alone).*

HEXAGONAL SYSTEM

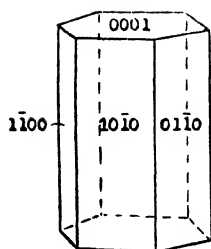


FIG. 55. Prism (m).
(First Order.)
e.g. Beryl (in combination with other forms).

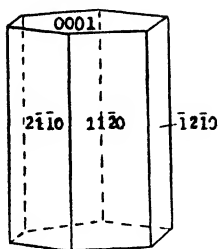


FIG. 56. Prism (a).
(Second Order.)

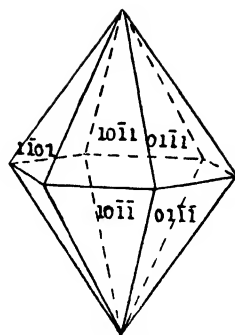


FIG. 57. Pyramid (p).
(First Order.)
e.g. Beryl (in combination with other forms).

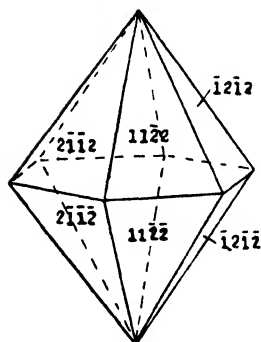


FIG. 58. Pyramid (s).
(Second Order.)
e.g. Beryl (in combination with other forms).

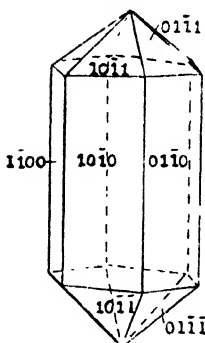


FIG. 59. Prism (m) and Pyramid (p).
(First Order.)
*e.g. Beryl, Apatite.
(Often with other forms.)
(After Dana.)*

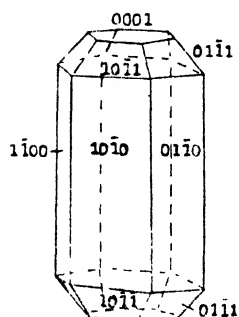


FIG. 60. Prism (m) and Pyramid (p) with base (c).
*e.g. Apatite.
(After Dana.)*

SEDIMENTARY PETROGRAPHY RHOMBOHEDRAL SYSTEM

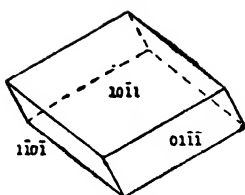


FIG. 61. Rhombohedron (r) (positive).

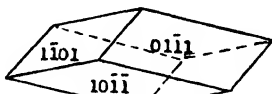


FIG. 62. Rhombohedron (r) (negative).

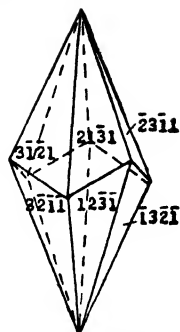


FIG. 63. Scalenohedron (v).

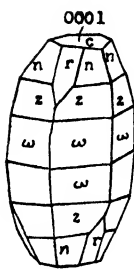


FIG. 64. *Corundum*. (After Dana.)
n (2243), z (2241), r (1011),
omega (14. 14. 28. 3)

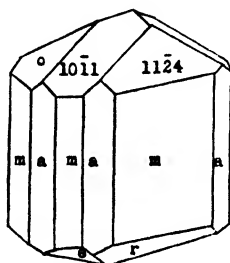


FIG. 65. *Tourmaline*. (After Dana.)
o (1124), r (1011), m (1010), a (1120), e (0112).

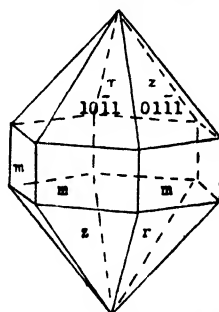


FIG. 66. Rhombohedra (r), (z), and Prism (m). e.g. *Quartz*

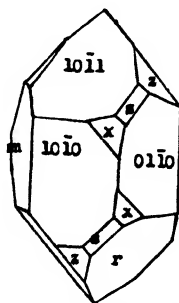


FIG. 67. *Quartz, right-handed*. (After Dana.)
r (1011), z (0111), s (1121),
x (5161), m (1010).

ORTHORHOMBIC SYSTEM.

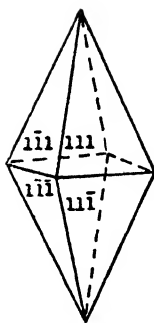


FIG. 68.
Pyramid (p).

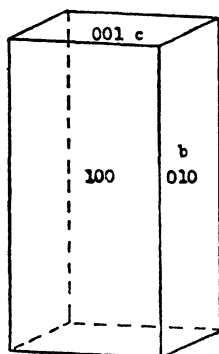


FIG. 69. Macropinacoid (100), Brachypinacoid (010) and Basal Pinacoid (001).

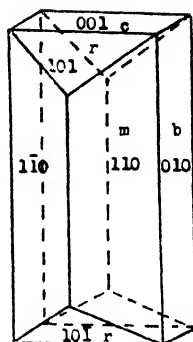


FIG. 70. Prism (m), Pinacoids (b), (c), and Macrodome (r).
e.g. Staurolite.

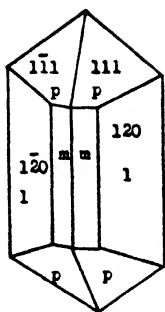


FIG. 71. Prisms (m) and (b) and Pyramids (p).
e.g. Topaz.
(After Dana.)

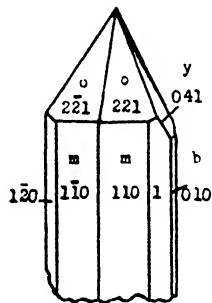


FIG. 72. Prisms (m) and (1) Pyramid (o), Brachydome (y).
e.g. Topaz.
(After Dana.)

MONOCLINIC SYSTEM

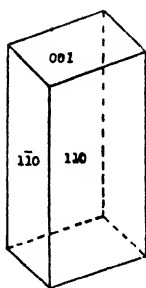


FIG. 73. Prism (m) and Basal Pinacoid (c).

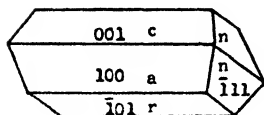


FIG. 74. Orthopinacoid (a), Pyramid (n), Basal Pinacoid (c), Orthodome (r).
e.g. Epidote.

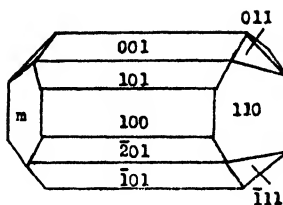


FIG. 75. *Epidote.*
(After Dana.)

TRICLINIC SYSTEM

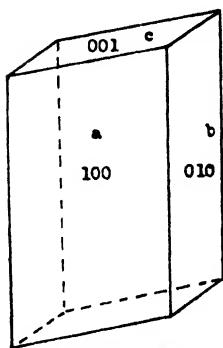


FIG. 76. Basal (c), Macro- (a) and Brachypinacoids (b).

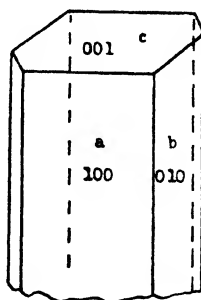


FIG. 77. As Fig. 76.
e.g. Kyanite.

Specific Gravity.—With many minerals this is a variable function depending on composition. Where one value alone is quoted it represents the average of several records. Where variation limits are persistent in the records, limiting values are given.

Lustre.—This property has reference not only to the appearance of the mineral in its native state but also in the detrital form as viewed normally by dark ground illumination under the microscope. In certain cases the reaction of the mineral to reflected polarised light is given.

Colour.—Colour depends to a large extent on composition and may be expected to vary accordingly. Colours quoted are in order of frequency and represent the tints to be anticipated from observation of the species. Generally the colour of detrital grains is paler than that of the parent mineral in bulk. The words “transparent,” “translucent” and “opaque” are added to indicate the common degree of visibility “through” the grain or otherwise when viewed under the microscope.

Magnetic Properties.—Detrital minerals are designated as “strongly,” “moderately,” “weakly” or “non-magnetic” (as the case may be), according to the conventional tests as described in Chapter V, p. 121.

Electrostatic Properties.—Detrital minerals are designated as “good,” “moderate,” “weak” or “non-conductors,” according to the conventional tests as described in Chapter V, p. 126.

Optical Properties.—(a) Refractive Index. The values throughout this book are quoted from E. S. Larsen and H. Berman¹ and have been compared with other authors. They are qualified as follows:—

<1.600	...	...	...	...	...	low.
>1.600 and <1.750	...	...	...	...	...	high.
>1.750	...	...	...	...	...	very high.

In all cases extreme limits, determined by variable composition, have been avoided, the values given being those of the normal mineral.

(b) Birefringence. The value represents the normal arith-

¹ *Op. cit.*

metric difference between the greater and the lesser R.I. figure. The qualification is according to E. S. Larsen and H. Berman.¹ "The birefringence is said to be weak if it is less than 0.010, moderate if between 0.010 and 0.025, strong if between 0.025 and 0.100, very strong if between 0.100 and 0.200, and extreme if greater than 0.200."

(c) The other optical characters are given in logical order, *e.g.* isotropic, uniaxial or biaxial character, position of optic axial plane, acute bisectrix etc. In a majority of cases these functions are quoted from A. N. Winchell.²

(d) Pleochroism where relevant is quoted in accordance with the generally recognised absorption scheme, qualified by the average colours noted for particular directions of light vibration.

(e) Anomalous optical properties where important are stated.

The data included in each case under "Optical Properties" must only be considered as a working summary. For more detailed information the student should refer to the authors cited and also to the standard texts by J. D. Dana,³ J. P. Iddings⁴ and A. N. Winchell.⁵

Characters in Sediments.—This has reference to the particular interpretation of sedimentary rock minerals with which we are concerned here, *i.e.* the modifications undergone by such minerals during their transference from parent rock to sedimentary deposit, alternatively during their growth *in situ* in certain well defined environments. Under this heading are included those peculiar collective properties by which detrital minerals achieve individuality, by which in fact they are correctly diagnosed under the microscope. Detrital mineral variations are legion; only constant experience with them in all kinds of deposits from world-wide sources can bring real competence in their identification and interpretation. The data given represent in practically every case the average results of the author's examination of a large and varied selection of

¹ *Op. cit.*, p. 33.

² "Elements of Optical Mineralogy." 3rd ed. Part 2 (Wiley, New York), 1933.

³ "System of Mineralogy." 6th ed. (Kegan Paul, London), 1892.

⁴ "Rock Minerals." (Chapman and Hall, London), 1906.

⁵ *Op. cit.*

examples, reinforced where appropriate with references to published observations of other petrographers.

Occurrence.—As far as possible the occurrences listed have reference to British sources and they are arranged in stratigraphical (ascending) order. In some cases where the mineral is scarce in British sediments, but none the less important in foreign environments, certain localities are given. In the latter connexion, as well as with the British records, individual authors are acknowledged, but in the case of some publications not easily available, the work of P. G. H. Boswell¹ has proved invaluable and to this the student is referred for more extensive records of occurrence.

Possible Sources of Derivation.—Provenance is suggested in every case and is of obvious importance in comprehensive investigation of a sediment. The parent rocks are noted in order of probability and the information given should aid palæogeographical reconstruction.

Remarks.—Any special features to be expected concerning the mineral species, its varieties, its possible confirmation by chemical or other means, are noted under this heading.

References.—References are to the "Occurrences" as listed previously. In addition certain general references are given where minerals, either in their native state or detrital developments, have been the subjects of intensive research.

The following is a complete list of the minerals, detrital and authigenic (including varieties), which are described in this chapter. These are arranged according to their systems of crystallisation. The subsequent text arrangement is alphabetical.

ISOMETRIC (CUBIC) SYSTEM.

Allophane (?).	Hercynite (Spinel Group).
Almandite (Garnet Group).	Magnetite (Spinel Group).
Analcite (Zeolite Group).	Melanite (Garnet Group).
Andradite (Garnet Group).	Periclase.
Ceylonite (<i>syn.</i> Pleonaste) (Spinel Group).	Picotite (Spinel Group).
Chromite (Spinel Group).	Pleonaste (<i>syn.</i> Ceylonite) (Spinel Group).
Diamond.	Pyrite.
Fluorite.	Pyrope (Garnet Group).
Galena.	Spessartite (Garnet Group).
Garnet (see varieties).	Sphalerite (<i>syn.</i> Zinc Blende).
Grossularite (Garnet Group).	Spinel (Spinel Group).
Halloysite.	Uvarovite (Garnet Group).

¹ "On the Mineralogy of Sedimentary Rocks." (Murby, London), 1933.

TETRAGONAL SYSTEM.

Anatase (<i>syn.</i> Octahedrite).	Viluite (<i>var.</i> Vesuvianite)
Cassiterite.	Xenotime.
Rutile.	Zircon.
Vesuvianite (<i>syn.</i> Idocrase).	

TRIGONAL (RHOMBOHEDRAL) SYSTEM.

Ankerite.	Magnesite.
Benitoite.	Menaccanite (<i>syn.</i> Ilmenite).
Calcite.	Quartz.
Corundum.	Ruby (<i>var.</i> Corundum).
Dolomite.	Sapphire (<i>var.</i> Corundum).
Graphite.	Siderite.
Hematite.	Tourmaline.
Ilmenite (<i>syn.</i> Menaccanite).	

HEXAGONAL SYSTEM.

Apatite.	Pyrrhotite.
----------	-------------

ORTHORHOMBIC SYSTEM.

Andalusite.	Humite (Humite Group).
Anhydrite.	Hypersthene (Pyroxene Group).
Aragonite.	Iddingsite.
Barite.	Lawsonite.
Beidellite (Montmorillonite-Beidellite Series). ¹	Marcasite.
Bronzite (<i>var.</i> Enstatite) (Pyroxene Group).	Montmorillonite (Montmorillonite-Beidellite Series).
Brookite.	Olivine (<i>syn.</i> Chrysolite) (Olivine Group).
Celestite.	Pyrophyllite.
Chiastolite (<i>var.</i> Andalusite).	Sillimanite.
Chrysolite (<i>syn.</i> Olivine) (Olivine Group).	Staurolite.
Chrysotile. ²	Steatite (<i>syn.</i> Talc). ⁴
Cordierite.	Strontianite.
Diaspore.	Sulphur.
Dumortierite.	Talc (<i>syn.</i> Steatite). ⁴
Enstatite (Pyroxene Group).	Thulite (<i>var.</i> Zoisite) (Epidote Group).
Fayalite (Olivine Group).	Topaz.
Goethite. ³	Zoisite (Epidote Group).

¹ Pseudohexagonal.² Dimorphous with antigorite (chlorite group), *g.v.*³ In some instances may be tetragonal. Also amorphous.⁴ Pseudohexagonal.

MONOCLINIC SYSTEM.

- Actinolite (Amphibole Group).
 Ægirine (Pyroxene Group).
 Allanite (*syn.* Orthite).
 Antigorite (Chlorite Group).
 Arfvedsonite (Amphibole Group).
 Augite (Pyroxene Group).
 Barkevicite (Amphibole Group).
 Basaltine (Basaltic Hornblende) (Amphibole Group).
 Bastite (*var.* Antigorite) (Chlorite Group).
 Biotite (Mica Group).
 Chlorite (Chlorite Group).
 Chloritoid (Chloritoid-Ottrelite Group).¹
 Clinocllore (Chlorite Group).
 Clinozoisite (Epidote Group).
 Crossite.
 Delessite (Chlorite Group).
 Diallage (*var.* Diopside) (Pyroxene Group).
 Dickite (Kaolin Group).
 Diopside (Pyroxene Group).
 Epidote (Epidote Group).
 Fuchsite.
 Gastaldite.
 Gibbsite (*syn.* Hydrargillite).
 Glaucanite.
 Glaucophane (Amphibole Group).
 Gypsum.
 Hiddenite (*var.* Spodumene) (Pyroxene Group).
 Hornblende (Amphibole Group).
 Jade (*syn.* Nephrite, *var.* Tremolite or Actinolite) (Amphibole Group).
 Kaolinite.
 Kunzite (Spodumene) (Pyroxene Group).
 Lepidolite (Mica Group).
 Lepidomelane (Mica Group).
 Monazite.
 Muscovite (Mica Group).
 Nephrite (*syn.* Jade, *var.* Tremolite or Actinolite) (Amphibole Group).
 Nontronite (Montmorillonite-Beidellite Series).
 Omphacite (*var.* Diopside) (Pyroxene Group).
 Orthite (*syn.* Allanite).
 Orthoclase (Felspar Group).
 Ottrelite (Chloritoid-Ottrelite Group).
 Penninite (Chlorite Group).
 Phlogopite (Mica Group).
 Piedmontite (Epidote Group).
 Riebeckite (Amphibole Group).
 Sanidine (Orthoclase Group).
 Selenite (*cryst.*) (Gypsum).
 Serpentine (Serpentine Group).
 Sphene (*syn.* Titanite).
 Spodumene (Pyroxene Group).
 Steatite (*syn.* Talc).²
 Talc (*syn.* Steatite).²
 Titanite (*syn.* Sphene).
 Tremolite (Amphibole Group).
 Triphane (*syn.* Spodumene).
 Wolframite.
 Wollastonite.

TRICLINIC (ANORTHIC) SYSTEM.

- Albite (Plagioclase Felspar Group).
 Andesine (Plagioclase Felspar Group).
 Anorthite (Plagioclase Felspar Group).
 Anorthoclase (Felspar Group).
 Axinite.
 Bytownite (Plagioclase Felspar Group).
 Enigmatite.
 Kyanite.
 Labradorite (Plagioclase Felspar Group).
 Microcline (Felspar Group).
 Oligoclase (Plagioclase Felspar Group).

AMORPHOUS MINERALS.

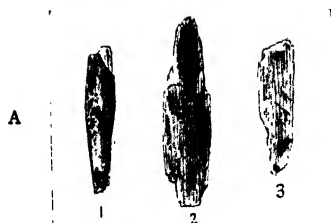
Commonly occurring amorphous minerals in sediments are as follows:—

- | | | |
|-------------|-------------|--------------|
| Agate. | Goethite. | Opal. |
| Chalcedony. | Halloysite. | Psilomelane. |
| Chert. | Jasper. | Pyrolusite. |
| Collophane. | Leucoxene. | |
| Flint. | Limonite. | |

¹ Monoclinic (pseudohexagonal) or may be triclinic.

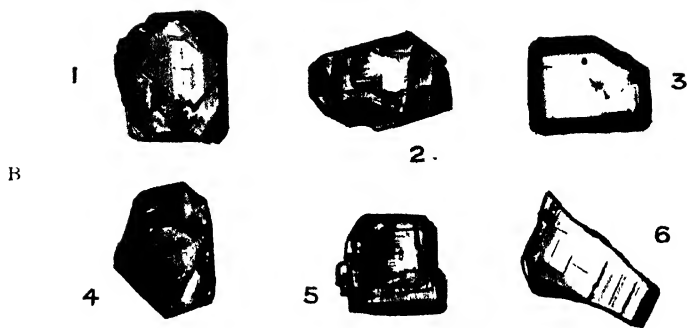
² ? Orthorhombic.

Attention is directed to the various tables of mineral constants (Appendices I—VIII) by which it is hoped considerable help will be afforded the student in rapidly checking a species of which he is doubtful, once he has ascertained certain specific optical properties. Mineral associations and significance of "index species" are not dealt with in this chapter but receive full discussion in Chapter XIII, which will be found to contain a great deal of supplementary information of use where diagnosis of one or more mineral species may lead to anticipation of paragenetic species likely to occur in the same sample, hence to sound conclusions regarding source of origin of the sediment in which they occur.

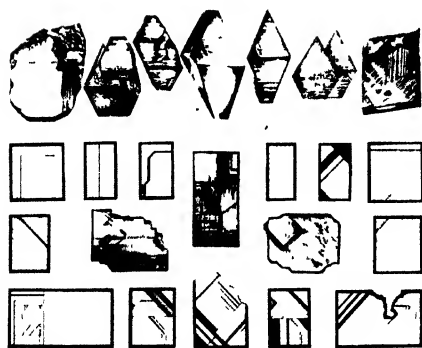


A. ACTINOLITE.

- 2, 3. Recent Sand, River Tigris, Iraq [x 40]
3. Shore Sand, Kynance, Cornwall [x 40]



B



C



D

B, C, D. ANVASE

- B. 1, 2, 3, 6. Pleocene Sands, St. Keverne, Cornwall (1, 3, x 120; 2, 6, x 70)
B. 4, 5. Tunbridge Wells Sand, Tunbridge Wells, Kent [x 70]
C. Typical Crystals and Fragments of Dartmoor Anvase (From brush drawings by
A. Brannall) Grade size, 0.2-1.4 mm
Top Row. Octahedrite. Unit pyramid, etc.
Remainder. Tabular, basal plane and (111), showing geometric patterning
D. Middle Jurassic, Yorkshure. (Anthegem) [x 105]

To face page 229.

PLATE 6

ACTINOLITE [Pl. 6 A, facing p. 229.] (AMPHIBOLE GROUP)

Chem. Comp. $2\text{CaO} \cdot 5(\text{Mg}, \text{Fe})\text{O} \cdot 8\text{SiO}_2 \cdot \text{H}_2\text{O}$.

System. Monoclinic.

Habit. Slender prisms, often euhedral.

Structure. Crystalline; individual crystals or fibrous aggregates.

Cleavage. Perfect \parallel (110), sometimes observed \parallel (100).

Fracture. Irregular.

Hardness. 5.

Spec. Grav. 3.0-3.3.

Lustre. Vitreous.

Colour. Bright green to grey-green; yellow. Transparent.

Mag. Prop. Weakly magnetic.

Elect. Prop. Moderate conductor.

Opt. Prop. R.I. high, $\alpha = 1.614$, $\beta = 1.630$, $\gamma = 1.641$. Birefringence strong, $\gamma - \alpha = 0.027$. Optically biaxial, negative. Optic axial plane \parallel (010). $Bxo = Z$ inclined at low angle to c axis; maximum extinction angle $Z \wedge c$ varies from 8° to 20° ; normally 16° . $2V = 80^\circ$. Prismatic grains slow \parallel length. $Y \parallel b$. Pleochroism moderate to weak: X=pale yellow, Y=yellow-green, Z=pale to dark green. Maximum absorption when vibrations are \parallel trace of Z. Dispersion, $p < v$ weak.

Characters in Sediments. Usually as distinctive yellowish-green, fibrous aggregates or single grains, some individuals being weakly pleochroic, others showing no reaction in this respect. The detrital varieties usually have a low extinction angle; they frequently show alteration to chloritic matter and contain iron-ore and carbonaceous inclusions.

Occurrence. New Red Sandstone of the West of England;¹ Upper Lias—Lower Inferior Oolite sands of the West of England;² Green-sand Bed at the Base of the Thanet Sand;³ Thanet Sands and Reading Beds of the London Basin;⁴ Miocene sands of Los Angeles Basin, S. California, and other foreign examples rich in amphibole minerals;⁵ from the Box-Stones occurring below and within the Pliocene Coralline and Red Craggs of Essex and Suffolk;⁶ later Tertiary deposits of the East of England;⁷ alluvium of R. Tigris;⁸ the Loess;⁹ in the Beach Sands of Cedar Point, Ohio;⁹ in association with dolomite in the sands at Fulford, East Yorkshire;¹⁰ in sands of the Kettleman Hills, California, U.S.A.¹¹

Possible Sources of Derivation. Crystalline schists; granular or massive metamorphic rocks; secondary alteration product of ferromagnesian silicates in igneous rocks.

REMARKS.—Not a common mineral in detrital sediments unless all types of fibrous hornblende are designated as actinolite. *Nephrite*, the pale to dark green fibrous variety of actinolite or tremolite (p. 340), is often known as *jade*.

References.

- ¹ H. H. Thomas, *Quart. Journ. Geol. Soc.*, 65, 1909, p. 235.
- ² P. G. H. Boswell, *Geol. Mag.*, 61, 1924, p. 252.
- ³ M. I. Gardiner, *Quart. Journ. Geol. Soc.*, 44, 1888, p. 755.
- ⁴ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 71, 1915, table IV.
- ⁵ Author's observations.
- ⁶ P. G. H. Boswell, *Geol. Mag.*, 1915, p. 250.
- ⁷ I. S. Double, *Proc. Geol. Assoc.*, 35, 1924, p. 335.
- ⁸ A. Viglino and G. Capeder, *Boll. Soc. geol. ital.*, 17, 1898, p. 81.
- ⁹ F. J. Pettijohn and J. D. Ridge, *Journ. Sed. Pet.*, 3, 1933, p. 92.
- ¹⁰ S. Melmore, *Naturalist*, 1929, p. 341.
- ¹¹ M. N. Bramlette, *Bull. Amer. Assoc. Pet. Geol.*, 18, 1934, p. 1559.

ÆGIRINE

(PYROXENE GROUP)

Chem. Comp. $\text{NaFeSi}_2\text{O}_6$ (A. N. Winchell).

System. Monoclinic.

Habit. Elongated prismatic crystals often with vertical striations and obtuse terminations. Twinning common on (100).

Structure. Crystalline.

Cleavage. Perfect \parallel (110). Parting noted on (010) or (001).

Fracture. Irregular.

Hardness. 6-6.5.

Spec. Grav. 3.5-3.55.

Lustre. Vitreous to resinous.

Colour. Leaf green, dark green to greenish black. Transparent to opaque.

Mag. Prop. Weakly magnetic.

Elect. Prop. Poor conductor.

Opt. Prop. R.I. high, $\alpha=1.742$, $\beta=1.768$, $\gamma=1.787$. Birefringence strong, $\gamma-\alpha=0.045$. Optically biaxial, negative. Optic axial plane \parallel (010). $Bxa=(X)$ makes small angle ($2^\circ-5^\circ$) with c in the obtuse angle β . $Y=b$. $2V=81^\circ$. Usually pleochroic: $X=\text{olive green}$ $>Y=\text{lighter shade}$ $>Z=\text{yellow green}$. Dispersion $\rho>\nu$, inclined.

Characters in Sediments. Ægirine is rare in sediments, owing to its relatively unstable character and is recorded principally from recent deposits, where it normally assumes yellow or olive green, prismatic features ("narrow green grains") with distinctive pleochroism. Careful measurement of its optical properties, notably the small extinction angle, negative sign and elongation, coupled with its characteristic colour and pleochroism, serve to distinguish it from hornblende or ordinary augite, two minerals with which it is at first glance liable to be confused.

Occurrence. In the Lower Cambrian, Massif de Stc. Croix, Central Poland;¹ in the Triassic iron-ores of Poland;² in the Lower Miocene of the San Onofre Breccia, California;³ in the Chinese Loess;⁴ in the dune sands of South Wales.⁵

Possible Sources of Derivation. Alkaline igneous rocks, particularly nepheline syenite and allied types.

References.

¹ P. Radziszewski, *Bull. Serv. Géol. Pologne*, 4, 1928, p. 500.

² W. Pawlica, *Bull. Serv. Géol. Pologne*, 1, 1920, p. 1.

³ A. O. Woodford, *Univ. California Publ., Bull. Dept. Geol. Sci.*, 15, 1925, p. 159.

⁴ H. T. Lee, *Bull. Geol. Soc. China*, 7, 1928, p. 191.

⁵ A. Stuart, *Proc. Geol. Assoc.*, 35, 1924, p. 323.

AGATE.

See Chalcedony, p. 261.

ALBITE

(PLAGIOCLASE FELSPAR GROUP)

Chem. Comp. $\text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$.**System.** Triclinic.**Habit.** Tabular, prismatic; commonly twinned on Albite law (010), Pericline law (about *b* axis); less commonly on Carlsbad law (about *c* axis), Baveno law (021) or Manebach law (001).**Structure.** Crystalline.**Cleavage.** Perfect \parallel (010) almost invariable; also \parallel (001). Less common \parallel (110). Parting \parallel (100).**Fracture.** Conchoidal, irregular.**Hardness.** 6.**Spec. Grav.** 2.61.**Lustre.** Vitreous, pearly.**Colour.** Colourless, grey.**Mag. Prop.** Non-magnetic.**Elect. Prop.** Non-conductor.**Opt. Prop.** R.I. low, $\alpha = 1.525$, $\beta = 1.529$, $\gamma = 1.536$. Birefringence moderate, $\gamma - \alpha = 0.011$. Optically biaxial, positive. Optic axial plane nearly \perp (010). $Bxa = Z$. Oblique extinction: $\perp X + 77^\circ$; $\perp Z + 21^\circ$; \parallel (001) $+ 3^\circ$; \parallel (010) $+ 20^\circ$. $2V = 74^\circ$. $2E = 134^\circ$. Dispersion weak, $p < v$.**Characters in Sediments.** Albite grains in sediments are almost always diagnosed by the presence of twin lamellæ, coupled with an R.I. practically the same as Canada balsam (sometimes slightly lower) and a superficial decomposition to muscovite and kaolinite. Otherwise distinction between them and other feldspars is in most cases impossible with single grains unless the crystal face presented can be determined and precise optical measurements made thereon. Inclusions are common, e.g. quartz, iron ores, zircon; also gaseous and liquid.**Occurrence.** In the Ordovician Grit of Anglesey;¹ in the Alpine Trias near Modane;² in the Upper Kimmeridge Clay—Portland Sand of Buckinghamshire etc.;³ in the Jurassic, Cretaceous and Eocene limestones of the Swiss Alps;⁴ in the Turonian Stage, Argentine;⁵ in the Flysch (Upper Cretaceous) limestone of the Pyrenees;⁶ in the later Tertiary deposits of East England;⁷ in the Dartmoor detritals.⁸**Possible Sources of Derivation.** Igneous Rocks.**REMARKS.**—Regular intergrowths of albite and orthoclase (p. 321) or microcline (p. 313) are known as *perthite* or *microperthite*.**References.**¹ E. Greenly and P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 88, 1932, p. 297.² G. Rose, *Pogg. Annalen Phys. Chem.*, 125, 1865, p. 457.³ E. Neaverson *Proc. Geol. Assoc.*, 35, 1924, p. 336.⁴ F. J. Kaufmann, *Beitr. Geol. Karte Schweiz*, 24, 1886, p. 581.⁵ L. Déverin, *Actes Soc. Helv. Sci. Nat.*, 1925, p. 138.⁶ J. de Lapparent, *C.R. Acad. Sci., Paris*, 167, 1918, p. 999.⁷ I. S. Double, *Proc. Geol. Assoc.*, 35, 1924, p. 336.⁸ A. Brammall, *Proc. Geol. Assoc.*, 39, 1928, p. 46.**General Reference.**H. L. Alling, "The Mineralogy of the Feldspars." *Journ. Geol.*, 31, 1923, p. 282, 353.

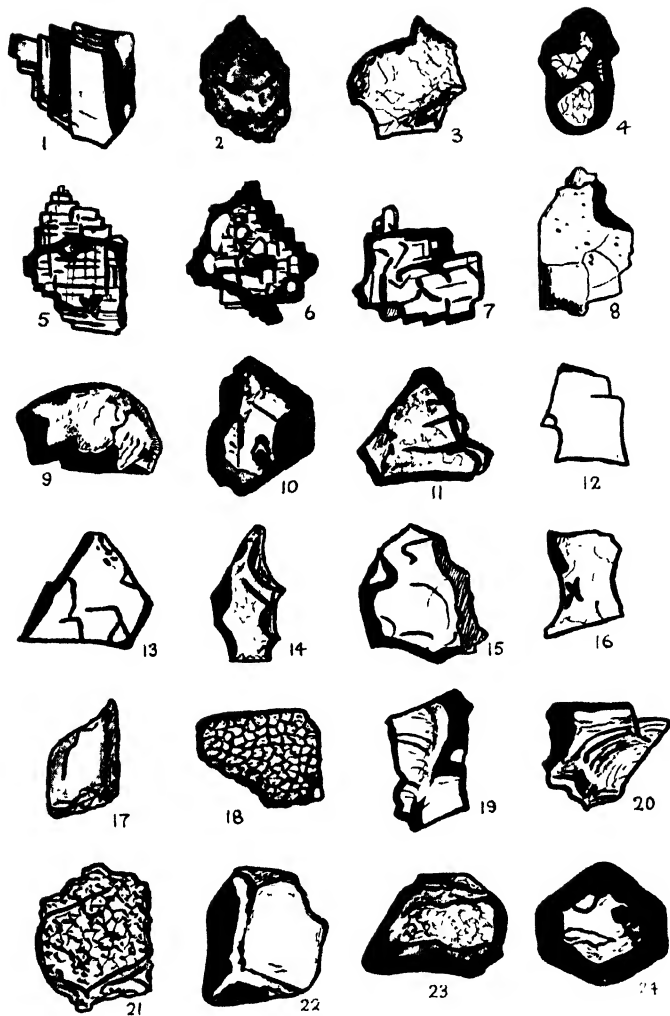
ALLANITE (Orthite)

(EPIDOTE GROUP)

Chem. Comp. $4(\text{Ca}, \text{Fe})\text{O}_3(\text{Al}, \text{Ce}, \text{Fe}, \text{Di})_2\text{O}_3 \cdot 6\text{SiO}_2 \cdot \text{H}_2\text{O}$.*System.* Monoclinic.*Habit.* Tabular || (100), elongated || b.*Structure.* Crystalline, massive.*Cleavage.* Poor || (001), (100), (110).*Fracture.* Irregular.*Hardness.* 6.*Spec. Grav.* 4.15 (decreases with alteration).*Lustre.* Vitreous, dull.*Colour.* Brown, black.*Mag. Prop.* ?*Elect. Prop.* ?*Opt. Prop.* Highly variable. R.I. high, $\alpha = 1.727$, $\beta = 1.739$, $\gamma = 1.751$.Birefringence moderate, $\gamma - \alpha = 0.024$. Optically biaxial, negative.Optic axial plane || (010). $Bxa = X \wedge c = 30^\circ - 40^\circ$. Or optic axialplane \perp (010), $X \wedge c = 22^\circ - 41^\circ$. $Y = b$. $2V = \text{large}$. Pleochroism : $X = \text{yellow or brown}$, $Y = \text{dark brown}$, $Z = \text{dark red brown}$. Disper-sion strong, $\rho > v$. Optically positive crystals also known, with vari-able R.I. ($\beta = 1.65 - 1.78 \pm$) and pleochroism $X = \text{colourless}$, $Z = \text{pale}$

green. Isotropic (altered) forms also known, of lower S.G. (3.4) and

R.I. $n = 1.61 \pm$.*Characters in Sediments.* Irregular grains, similar to epidote in detrital form, but liable to show considerable variation in appearance due to alteration products. Colour and other physical properties may vary greatly in the same grains. May be intimately associated with epidote. The optical variations are such that great care is necessary in diagnosis, which is not always directly possible by microscopical means alone.*Occurrence.* In borehole samples, Viareggio, Italy;¹ in borehole samples from the Plain of Lombardy;² in the black sands of Idaho;³ in submarine deposits of the Arctic Ocean.⁴*Possible Sources of Derivation.* Acid igneous rocks. Metamorphic rocks. Certain iron ores.**REMARKS.**—Allanite is not a common species and its occurrence in sediments will be localised in environments which are favourably placed as regards appropriate source of origin of detritus.*References.*¹ I. Chelussi, *Boll. Soc. Geol. ital.*, 43, 1924, p. 17.² *Op. cit.*, p. 161.³ E. V. Shannon, *Proc. U.S. National Mus.*, 60, 1921, p. 1.⁴ J. Thoulet, *C.R. Acad. Sci., Paris*, 148, 1909, p. 884.**ALLOPHANE***Chem. Comp.* $\text{Al}_2\text{O}_3 \cdot \text{SiO}_2 \cdot n\text{H}_2\text{O}$.*System.* Isometric or amorphous.*Habit.* White amorphous powder. Often colloidal.*Structure.* Massive, encrustations.*Cleavage.* None.*Fracture.* None.



ALMANDINE GARNET FROM DIFFERENT

- 1 Torridonian (after Bosworth)
- 2 Quartzite (Cambrian) Malvern
- 3 Holfkush Sandstone (Cambrian), Malvern
- 4 May Hill Sandstone (Silurian) Malvern
- 5 Millstone Grit, Northumberland
- 6 Fine clay, Coal Measures, Leighton, Parky, N.B.
- 7 Pennine, Lynemouth, Northumberland
- 8 Bunter, Hoxlake, Cheshire
- 9 Lias, Npton, Rugby
- 10 Northampton Sands, Northampton

BRITISH STRATIGRAPHICAL HORIZONS

- 11 Corallum, Abbotshury, Dorset
- 12 Portland Sand, Portland, Dorset
- 13 Ashdown Sand (Wealden) Hastings, Sussex
- 14 Upper Greensand, Fildsworth, Essex
- 15 Thanet Sand, Plumstead, Kent
- 16 Woolwich and Reading Sand, St. Albans
- 17 Blackheath Beds, Elmstead, Surrey
- 18 Bugshot Sands, Bournemouth
- 19 Pliocene, Bentley, Suffolk
- 20 Glacial Sand, Kington, Herts
- 21 Shore Sand, Speeton, Yorks.

[All x 5.]

Hardness. 3.

Spec. Grav. 1.86.

Lustre. Earthy.

Colour. Blue, green, white.

Mag. Prop. ?

Elect. Prop. ?

Opt. Prop. R.I. low, $n = 1.49$. Optically isotropic.

Characters in Sediments. Identified in encrusting masses in certain clay deposits and characterised by its colour, softness, low S.G. and R.I.

Occurrence. In the clays of Maryland, U.S.A.¹

Possible Sources of Derivation. Ball clay, china clay, shale, Fuller's earth, coal.

Reference.

¹ H. Ries, *Maryland Geol. Surv.*, 4, 1902, p. 215.

General References.

C. S. Ross and P. F. Kerr, "Halloysite and Allophane." *U.S. Geol. Surv., Prof. Paper* 185-G, 1934.

C. S. Ross and P. F. Kerr, "The Clay Minerals and their Identity" *Journ. Sed. Pet.*, 1, 1931, p. 55.

ALMANDITE

[Pl. 7, facing p. 233.]

(GARNET GROUP)

Chem. Comp. $\text{Fe}_3\text{Al}_2\text{Si}_3\text{O}_{12}$.

System. Isometric.

Habit. Dodecahedron (110), trapezohedron (211) or combination of both forms. No twinning.

Structure. Crystalline, massive.

Cleavage. Usually none; poor \parallel (110).

Fracture. Irregular, subconchoidal.

Hardness. 7.

Spec. Grav. 4.1-4.3.

Lustre. Vitreous, resinous

Colour. Red.

Mag. Prop. Moderately magnetic.

Elect. Prop. Poor conductor.

Opt. Prop. R.I. very high, $n = 1.766 - 1.830$. Optically isotropic, though some examples rarely yield anomalous interference tints due to strain.

Characters in Sediments. Detrital almandite is commonly irregular, often fractured, sometimes well rounded; generally devoid of recognisable crystal faces. Platy grains determined by a poor (110) cleavage, showing subconchoidal fracture and prominent re-entrant angles sometimes met with. Inclusions common, e.g. quartz, iron ore; in the Dartmoor detritals A. Brammall has recorded quartz, feldspar, apatite, zircon, biotite, rutile, iron ore. Note particularly surface characteristics: many detrital almandite grains provide distinctive features, e.g. pitting, grooving, spotting, rectangular patterning, deep colour staining and sometimes "etched" appearance.

Occurrence. Almandite is the most widespread and persistent variety of garnet in detrital sediments and in the British Isles is found in the oldest to the youngest rocks with few exceptions. Among the best horizons for this variety are:—Old Red Sandstone, Herefordshire; Calciferous Sandstone, Midlothian region, Scotland; Millstone Grit, Northumberland, Durham and Yorkshire; Permian rocks, South

Devonshire; Upper Keuper, Leicestershire; Estuarine Sandstones, Yorkshire and Northamptonshire; various Glacial Sands and Gravels of East Anglia, Plateau Gravels of the London Basin and shore sands of West Cornwall (Marazion, St. Ives). (N.B.—The comparative scarcity of garnet in the Tertiary deposits of Cornwall is noteworthy: see reference * below.)

Possible Sources of Derivation. Igneous and metamorphic rocks, particularly crystalline gneisses and schists. Alluvial deposits.

REMARKS.—Almandite varies widely in detrital sediments, specific physical features often typifying grains from definite horizons; on this account it is of great importance for correlation purposes and also for suggesting the conditions under which deposition took place.

General References.

- T. O. Bosworth, "Keuper Marls around Charnwood." *Leicester Lit. and Phil. Soc.*, 1913, p. 96 and *Figs.* 44, 45.
 *P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 79, 1923, p. 221.
 C. Raeburn and H. B. Milner, "Alluvial Prospecting." (Murby, London), 1927, p. 389 and *Pl.* 16 (for alluvial occurrences).
 A. Stuart, *Proc. Geol. Assoc.*, 35, 1924, p. 321 and *Fig.* 27.
 A. Brammall, *Proc. Geol. Assoc.*, 39, 1928, p. 35.
 L. Hawkes and J. A. Smythe, "Garnet-bearing Sands of the Northumberland Coast." *Geol. Mag.*, 68, 1931, p. 345.

ANALCITE

(ZEOLITE GROUP)

Chem. Comp. $\text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 4\text{SiO}_2 \cdot 2\text{H}_2\text{O}$.

System. Isometric. ?Pseudoisometric.

Habit. Trapezohedral; complex penetration, twins.

Structure. Crystalline, massive.

Cleavage. Difficult cubic cleavage

Fracture. Irregular.

Hardness. 5-5.5.

Spec. Grav. 2.2-2.29.

Lustre. Pearly.

Colour. White, grey, greenish white.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low, $n = 1.487$. Isotropic but sometimes optically anomalous. Some crystals are uniaxial, R.I. low, $\epsilon = 1.486$, $\omega = 1.487$; negative sign. Biaxial crystals also known having very small optic axial angle and weak birefringence, $\gamma - \alpha = 0.001$; such crystals have negative sign.

Characters in Sediments. Detrital analcite is a rare and local constituent of sediments, chiefly of recent date. It occurs in angular to sub-angular, polygonal grains, difficult of identification without close optical tests. Its low R.I., lack of colour and isotropism serve to suggest a member of the zeolite group, but confusion with certain forms of leucite and sodalite (in small grains) may be easy unless chemical tests are applied. It readily gelatinises with HCl and gives strong sodium reaction to flame test.

Occurrence. Middle Cretaceous clays of Duinzen;¹ Eocene Lake-bed deposits of Utah and Colorado, U.S.A.;² Quaternary Lake Beds of playa deposits of Arizona, U.S.A.;³ deep sea deposits.⁴

Possible Sources of Derivation. From igneous rocks, particularly basic hypabyssal and volcanic types and amygdaloidal forms of the latter (cavities filled with zeolites): e.g. analcite dolerite and analcite basalt.

References.

- ¹ K. von Seebach, *Georg. Augustus Univ., K. Gesellsch. Wiss. Göttingen. Nachr.*, 1862, p. 334.
- ² W. H. Bradley, *U.S. Geol. Surv., Prof. Paper* 158-A, 1929.
- ³ C. S. Ross, *Amer. Min.*, 13, 1928, p. 195.
- ⁴ H.M.S. Challenger, Report on Scientific Results of the Voyage. (Admiralty), 1891.

ANATASE (Octahedrite)

[Pl. 6 B, C, D, facing p. 220.]

Chem. Comp. TiO_2 .

System. Tetragonal.

Habit. Octahedral, acute or obtuse; often tabular.

Structure. Crystalline, rarely massive.

Cleavage. Perfect || (001) and (111).

Fracture. Subconchoidal, uneven.

Hardness. 5.5-6.

Spec. Grav. 3.82-3.95.

Lustre. Adamantine, submetallic.

Colour. Yellow, brown, indigo-blue, black. Transparent to opaque.

Mag. Prop. Non-magnetic.

Elect. Prop. Moderately good conductor.

Opt. Prop. R.I. very high, $\omega = 2.554$, $\epsilon = 2.493$. Birefringence strong, $\omega - \epsilon = 0.061$. Optically uniaxial, negative. Non-pleochroic except in thick grains: ω = pale blue or yellow, ϵ = dark blue or orange. Basal sections isotropic. Occasionally in the darker coloured varieties a biaxial figure with small optic axial angle is observed.

Characters in Sediments. Tabular (basal) grains are most common (001), often bevelled by (111) faces. Such grains exhibit interference figure. Parallel intergrowth of tabular varieties common. Pyramidal forms, simple or compound, also observed; these may show striations || intersection with prism (110). Less common are the angular cleavage flakes or irregularly fractured grains. Two distinct coloured varieties are met with, the yellow or yellow-brown and the indigo-blue or greenish-blue types. Dark coloured grains are almost metallic and opaque. Inclusions of quartz, tourmaline, zircon, rutile, cassiterite, iron-ores have been noted. Zoning or "geometric patterning" frequent in some developments: see under "Remarks" on p. 236. Both primary and secondary grains occur, sometimes in the same deposit; the latter are probably derived *in situ* from the decomposition of titaniferous minerals such as ilmenite and usually show marked **euhedrism**. The former are detrital, evinced by a certain degree of wear (rounding) consequent on prolonged abrasion.

Occurrence. In Ordovician sediments;¹ in Devonian grits, slates etc. of the Torquay district, Devonshire;² in the Old Red Sandstone of the West Midlands;³ in the Permo-Triassic rocks of the Midlands;⁴ in the Bunter Pebble Bed of the West of England;⁵ in the New Red Sandstone of the West of England;⁶ in the Upper Lias—Lower Inferior

Oolite sands of the West of England;⁷ in the Kellaways Rock (Oxfordian) of the Peterborough District;⁸ in the Wealden Sands (Lower Cretaceous) of Tunbridge Wells and other areas in the Weald;⁹ in Cretaceous sands of the Haldon Hills etc., West of England;¹⁰ in the Bagshot Beds (Eocene) of Essex;¹¹ in the Pliocene sands, St. Keverne, Cornwall;¹² in later Tertiary deposits of Eastern England;¹³ in alluvial sands, Dartmoor, Devonshire;^{14, 15} in certain surface deposits of S.E. Devonshire.¹⁶

Possible Sources of Derivation. Crystalline igneous and metamorphic rocks; when abundant probably authigenic, derived *in situ* from decomposition of ilmenite or other titaniferous species: see reference 14.

REMARKS.—The mineralogy and geochemistry of anatase have been very fully discussed by A. Brammall and H. F. Harwood in connexion with its occurrence at Dartmoor, while in a later contribution the former author figures and describes some beautiful examples of both zoned tabular and pyramidal types found in Dartmoor detrital deposits; both these papers should be consulted for this interesting mineral (see references^{14, 15}).

References.

- ¹ P. G. H. Boswell, *Proc. Liverpool Geol. Soc.*, 14, 1924, p. 14.
- ² W. G. Shannon, *Proc. Geol. Assoc.*, 39, 1928, p. 137.
- ³ W. F. Fleet, *Geol. Mag.*, 63, 1926, p. 513.
- ⁴ W. F. Fleet, *Proc. Geol. Assoc.*, 38, 1927, p. 1.
- ⁵ H. H. Thomas, *Quart. Journ. Geol. Soc.*, 58, 1902, p. 622 and *Pl.* 32.
- ⁶ H. H. Thomas, *Quart. Journ. Geol. Soc.*, 65, 1909, p. 231.
- ⁷ P. G. H. Boswell, *Geol. Mag.*, 61, 1924, p. 254.
- ⁸ E. Neaverson, *Proc. Geol. Assoc.*, 36, 1925, p. 23.
- ⁹ H. B. Milner, *Proc. Geol. Assoc.*, 34, 1923, *Pl.* 5 and p. 200; also 36, 1925, p. 315.
- ¹⁰ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 70, 1923, p. 209, 218.
- ¹¹ S. W. Wooldridge, *Proc. Geol. Assoc.*, 35, 1924, p. 377.
- ¹² H. B. Milner, *Quart. Journ. Geol. Soc.*, 78, 1922, p. 363.
- ¹³ I. S. Double, *Proc. Geol. Assoc.*, 35, 1924, p. 238.
- ¹⁴ A. Brammall and H. F. Harwood, *Mineral. Mag.*, 20, 1923, p. 20.
- ¹⁵ A. Brammall, *Proc. Geol. Assoc.*, 39, 1928, p. 30.
- ¹⁶ W. G. Shannon, *Geol. Mag.*, 64, 1927, p. 147.

General Reference.

- J. A. Butterfield, "An Occurrence of Anatase in the Millstone Grit of Yorkshire." *Trans. Leeds Geol. Assoc.*, 5, 1934-5, p. 142

ANDALUSITE [Pl. 8 A, facing p. 236.]

Chem. Comp. $\text{Al}_2\text{O}_3 \cdot \text{SiO}_2$. Fe and Mn may be present.

System. Orthorhombic.

Habit. Prismatic, rarely euhedral, square prisms, acicular or fibrous.

Structure. Usually crystalline.

Cleavage. Perfect || (110), imperfect || (100), more rarely || (010).

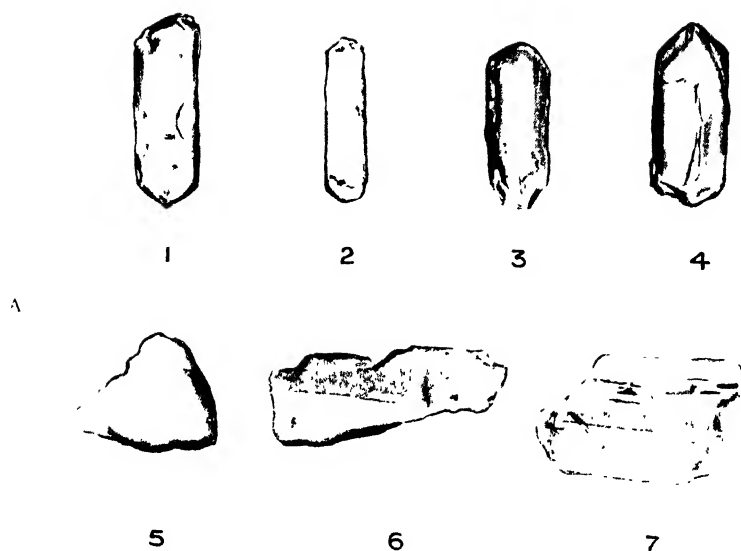
Fracture. Uneven and irregular.

Hardness. 7-5.

Spec. Grav. 3.1-3.2.

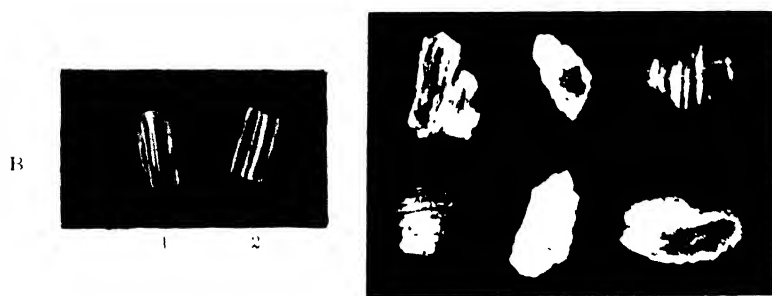
Lustre. Vitreous.

Colour. Colourless, white and pale shades of red, green, brown and violet. Transparent to translucent.



A. ANDALUSITE

- 1, 4. Phlocine Sands, Cornwall
 2, 3. Blown Sands, Newgate, Pembroke-hire
 5, 6, 7. Phlocine Sand, Cornwall (All x 60)



B, C. ANDESINE

- B, 1. Torridon Sandstone, Skye, N.B. (x 30)
 2. Abbotsbury Iron Ore (Corallham), Abbotsbury, Dorset (x 30)
 C. 1. Brahmaputra Sands, India (x 42)
 (Ill. x Nichols)

Mag. Prop. Non-magnetic.

Elect. Prop. Bad conductor.

Opt. Prop. R.I. high, $\alpha = 1.634$, $\beta = 1.639$, $\gamma = 1.643$. Birefringence weak, $\gamma - \alpha = 0.009$. Optically biaxial, negative. $2V = 85^\circ$. Length fast. Optic axial plane $\parallel (010)$. $Bxa \perp (001)$. $Bxa = X \parallel c$; $Y \parallel b$, $Z \parallel a$. Straight extinction \parallel prism-edge. Pleochroism intense in some varieties; $X > Y$ or Z ; Y and Z colourless, X rose or blood-red. Dispersion weak, $\rho > \nu$.

Characters in Sediments. Colourless, "glassy"; sometimes with pinkish tinge; grains very variable in form; commonly irregular and sub-angular, but prismatic types also met with. Frequently shows presence of inclusions of graphite or carbonaceous matter,[†] also alteration products such as sericite or kaolinite, all causing a turbid appearance of the mineral. These features and its negative sign serve to differentiate andalusite from topaz (with which it may sometimes be confused), but the pink to blood-red pleochroism of the former, when present, is an infallible guide.

Occurrence. In Millstone Grit of Yorkshire;¹ in Cretaceous and Eocene sands of the Oxford district;² in the Cretaceous and Tertiary deposits of the West of England;³ in the Pliocene deposits of St. Keverne, Cornwall;⁴ in the sands of Pliocene age at St. Agnes Beacon, Newquay;⁵ in the later Tertiary deposits of the East of England;⁶ in the Pliocene deposits of Sanderstead, Surrey;⁷ in the ferruginous sands of Netley Heath, Surrey;⁸ in the Pliocene deposits of Cornwall and Lenham, Kent;⁹ in the Dartmoor detritals;¹⁰ in the surface deposits of S.E. Devonshire;¹¹ in the shore sand of St. Ives Bay, Cornwall.¹²

Possible Sources of Derivation. Granites and contact metamorphic rocks.

REMARKS.—At one time detrital andalusite was thought to be restricted to Tertiary deposits in the British Isles, but as the references above show, it ranges back at least as far as Cretaceous sediments, probably to Palæozoic. It certainly gets extremely rare with increasing geological age of sedimentary rocks and may be looked for almost universally in Pliocene deposits, according to the author's observations. See also references to chiastolite occurrences on p. 263, paragraph on p. 504, and reference ¹³ below.

The manganese-bearing variety, manganandalusite or viridine, is characterised by its dark green colour, yellow-green pleochroism and high R.I., $\alpha = 1.662$, $\beta = 1.671$, $\gamma = 1.691$ (A. N. Winchell). This variety has not so far been recorded from sediments.

† Chiastolite: see p. 263.

References.

- ¹ A. Gilligan, *Quart. Journ. Geol. Soc.*, 75, 1919, p. 251.
- ² G. M. Davies, *Mineral. Mag.*, 17, 1915, p. 218.
- ³ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 79, 1923, p. 205.
- ⁴ H. B. Milner, *Quart. Journ. Geol. Soc.*, 78, 1922, p. 363.
- ⁵ J. S. Flett, *Mem. Geol. Surv.*, Great Britain Sheet 346, 1906, p. 63.
- ⁶ I. S. Double, *Proc. Geol. Assoc.*, 35, 1924, p. 339.
- ⁷ F. Gossling and S. W. Wooldridge, *Proc. Geol. Assoc.*, 37, 1926, p. 92.
- ⁸ P. G. H. Boswell, in H. G. Dines and F. H. Edmunds, "Geology of the Country Arcund Aldershot and Guildford." *Mem. Geol. Surv.*, Great Britain, 1929, p. 114.
- ⁹ H. H. Thomas, *Mineral. Mag.*, 15, 1909, p. 241.
- ¹⁰ A. Brammall, *Proc. Geol. Assoc.*, 39, 1928, p. 27.
- ¹¹ W. G. Shannon, *Geol. Mag.*, 64, 1927, p. 145.
- ¹² T. Crook and G. M. Davies, *Geol. Mag.*, 1909, p. 120.
- ¹³ P. G. H. Boswell, "The Rarer Minerals of British Sedimentary Rocks." *Trans. Geol. Soc. Glasgow*, 18, 1926-27, p. 133.

ANDESINE [Pl. 8 B, c, facing p. 236.]

(PLAGIOCLASE FELSPAR GROUP)

Chem. Comp. Ab_3An_2 . ($\text{Ab} = \text{Na}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$. — $\text{An} = \text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$).**System.** Triclinic.**Habit.** Tabular, prismatic. Polysynthetic twinning on (010) almost invariable (Albite law); also Pericline law (about b axis); Carlsbad law (about c axis); Baveno law (021); Manebach (001).**Structure.** Crystalline; massive.**Cleavage.** Perfect || (001) and (010); indifferent || (110). Parting || (100).**Fracture.** Irregular.**Hardness.** 6.**Spec. Grav.** 2.68.**Lustre.** Pearly.**Colour.** Colourless.**Mag. Prop.** Non-magnetic.**Elect. Prop.** Non-conductor.**Opt. Prop.** R.I. low, $\alpha = 1.550$, $\beta = 1.553$, $\gamma = 1.557$. Birefringence weak, $\gamma - \alpha = 0.007$. Optically biaxial positive. Oblique extinction: $X' \wedge (010) = \text{max. } 25^\circ$; on 010 $X' \wedge (001) = 8^\circ$; on 001 $X' \wedge (010) = 2^\circ$. Optical properties variable with composition. $2V = 88^\circ$. Dispersion about bxa , $\rho > v$.**Characters in Sediments.** Detrital andesine is probably more common in sediments than records seem to indicate. Grains may be expected to be of irregular shape, clear, colourless and with characteristic twinning. Accurate diagnosis depends on being able to determine the crystallographic orientation of the grain under observation, otherwise distinction from oligoclase or albite may not be possible. The R.I. may afford a clue, being *lower* than Canada balsam for these minerals and *higher* for andesine. Decomposition products include sericitic mica, kaolinite and complex hydrous aluminium silicates. Inclusions common, quartz, iron ores, zircon, gaseous or liquid. Occasional zoning.**Occurrence.** In the Old Red Sandstone of the Cardiff district;¹ in the soils of Java;^{2, 3} in sands at Kettleman Hills, California, U.S.A.⁴**Possible Sources of Derivation.** Igneous rocks, particularly intermediate hypabyssal and volcanic types.**References.**¹ A. Heard and R. Davies, *Quart. Journ. Geol. Soc.*, 80, 1924, p. 499.² G. A. Neeb, *Overdruk uit de Handelingen v/h 7de Nid. Ind. Natuurrwet.*, *schappelijk Congres*, 1936, p. 695.³ D. A. Carroll, *Journ. Roy. Soc., West Australia*, 20, 1933-4, p. 100.⁴ N. M. Bramlette, *Bull. Amer. Assoc. Petrol. Geol.*, 18, 1934, p. 1562.**ANDRADITE**

(GARNET GROUP)

Chem. Comp. $3(\text{Ca}, \text{Mg}, \text{Fe})\text{O} \cdot \text{Fe}_2\text{O}_3 \cdot 3\text{SiO}_2$.**System.** Isometric.**Habit.** Dodecahedral (110), trapezohedral (211) or combination of both. Twinning unknown.**Structure.** Crystalline.**Cleavage.** None.**Fracture.** Irregular.

Hardness. 7.

Spec. Grav. 3.78.

Lustre. Vitreous.

Colour. Variable, yellow, brown, green, black.

Mag. Prop. Moderately magnetic.

Elect. Prop. Poor conductor.

Opt. Prop. R.I. very high, $n = 1.865$. Isotropic, but sometimes optically anomalous: biaxial with high interference tints.

Characters in Sediments. A rare constituent of sediments, characterised by yellow to green colour, very high R.I. and tendency to dodecahedral habit. Incipient alteration to epidote, calcite or feldspar characteristic; in the more ferriferous type, to limonite. Zoning observed in some examples.

Occurrence. In the Silurian Rocks of Scotland.¹

Possible Sources of Derivation. Contact metamorphosed limestone; schist; syenites.

REMARKS.—See also *melanite*, the black variety of andradite (p. 312).

Reference.

¹ W. Mackie, *Rep. Brit. Assoc.*, 1928 (*Glasgow*), 1929, p. 556.

ANHYDRITE

[Pl. 9, facing p. 240.]

Chem. Comp. CaSO_4 .

System. Orthorhombic.

Habit. Prismatic, tabular, fibrous (radial, spherulitic), granular and as rectangular cleavage flakes. Also twinned about (012) and lamellar (101).

Structure. Crystalline, massive; curvilinear.

Cleavage. Three pinacoidal directions: very perfect \parallel (001) and (010); less perfect \parallel (100); the three when developed give rise to square-shaped flakes.

Fracture. Irregular, splintery.

Hardness. 3-3.5.

Spec. Grav. 2.899-2.985. (Note difference from Gypsum, p. 293.)

Lustre. Pearly on (001) flakes; vitreous on (010) and (100) flakes. Sometimes resinous.

Colour. Colourless, white, grey, pink or bluish-white. Colourless in thin grains or sections.

Mag. Prop. Non-magnetic.

Elect. Prop. Poor conductor.

Opt. Prop. R.I. variable, $\alpha = 1.570$, $\beta = 1.575$, $\gamma = 1.614$. Birefringence strong, $\gamma - \alpha = 0.044$. Biaxial positive. $2V = 42^\circ$. Optic axial plane \parallel (010). $Bxa \perp$ (100). $Bxa = Z$. $X \parallel c$, $Y \parallel b$, $Z \parallel a$. Straight extinction. Non-pleochroic. Dispersion $\rho < v$.

Characters in Sediments. Extremely variable in form, some of the principal varieties being shown in Pl. 9. An interesting, but little known species as free crystalline grains. Diagnosed chiefly by its S.G., R.I. (a certain amount of "twinkling" is observed in many examples), cleavages and positive optical character. Liable to confusion with barite, sometimes kyanite, topaz, sillimanite, possibly enstatite. Distinguish by careful S.G. and optical tests, also (if necessary) with HCl which causes no effervescence on solution, thus differentiating it from all carbonates. Well cleaved, rectangular grains

exhibit remarkable cubic appearance and are unique in development. Note that (001) cleavage flakes will yield a biaxial figure (emergence of *bxo*) which is "central," in contrast with figure yielded by calcite (eccentric or partial). Aggregates and compound grains also observed. Inclusions of iron-ores common; zoning developed in occasional types; see *Pl. 9*, nos. 11-14. In appropriate circumstances anhydrite grains exhibit every stage in alteration to gypsum, the most notable features being loss of crystal form and relief (decreased R.I.), change of optical properties and sometimes the formation of definite selenite crystals (p. 293).

Occurrence. In the Lower Devonian Sediments, Michigan, U.S.A.;¹ in Miocene sands and marls, Iraq and Iran;² in oil-well samples, Egypt;³ in sands of the Kettleman Hills, California, U.S.A.⁴

Possible Sources of Derivation. Invariably authigenic; occurs mainly in association with limestones from which it can be formed by replacement (metasomatism). Also occurs with rock-salt and, contrary to usual belief, co-exists with gypsum in the same deposit.

REMARKS.—Haloanhydrite is a peculiar species compounded of rock-salt and anhydrite.

References.

¹ S. W. Alty, *Rep. Brit. Assoc. (York)*, 1932, p. 330.

² Author's observations.

³ T. S. Bowman, "Report on Boring for Oil in Egypt." Section iii, *Mines and Quarries Dept., Egypt*, 1931.

⁴ M. N. Bramlette, *Bull. Amer. Assoc. Petrol. Geol.*, 18, 1934, p. 1559.

General Reference.

L. Cayeux, "Introduction à l'étude pétrographique des Roches Sédimentaires." Paris, 2nd ed. 1931.

ANKERITE

Chem. Comp. $\text{CaO} \cdot (\text{Mg}, \text{Fe}) \text{O} \cdot 2 \text{CO}_2$.

System. Trigonal.

Habit. Rhombohedral, often curved.

Structure. Crystalline or massive.

Cleavage. Perfect $\parallel (10\bar{1}1)$.

Fracture. Irregular, rare.

Hardness. 3-4.

Spec. Grav. 2.95-2.97.

Lustre. Vitreous, pearly.

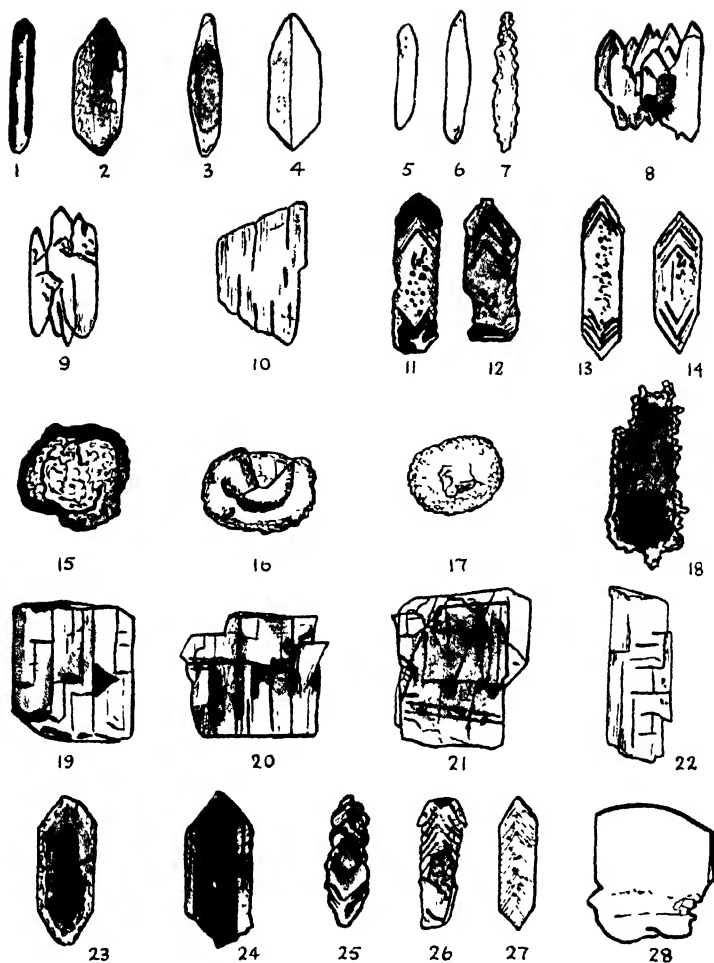
Colour. White, yellow, brown.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. varies with FeCO_3 content, low for ϵ , high for ω . FeCO_3 , 10%, $\omega = 1.698$, $\epsilon = 1.518$; FeCO_3 , 22%, $\omega = 1.716$; $\epsilon = 1.526$. Birefringence very strong, $\omega - \epsilon = 0.180$, 0.190. Optically uniaxial, negative. $(10\bar{1}1)$ cleavage flakes show partial interference figure.

Characters in Sediments. Occurs usually in irregular, often curvilinear, rhombohedral grains, white to brown in colour and with marked R.I. variations. Diagnosed chiefly by these characteristics, also strong "twinkling" effect on rotation of polariser alone. It is desirable to confirm diagnosis by chemical tests for ferrous carbonate content.



ANHYDRITE

All from the Lower Ears (Miocene) of Iraq and Iran.

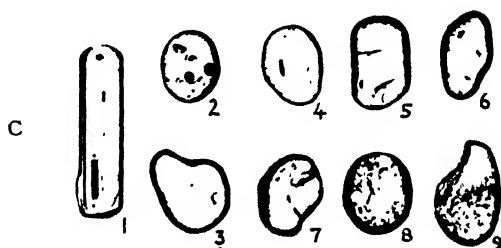
- 1-4 "Fulcrum" type "Denticular" types
- 5-9 Composite "shell" type 10 "Fibrous" type
- 11-14 "Zoned" types 15-16 "Oolite" types
- 17 "Fished" or "ragged" type
- 18-21 Rectangular (Pseudo-cubic) cleaved types
- 22 "Kyanite" type 23-24 "With dark cores"
- 25 "Herring bone" type 26-28 "Glass cleavage" (All x 25)

N.B. Nos. 10-14, 18, 25-27 show partial alteration to gypsum



A, B. ANORTHOCASE

- A Fuller's Earth (Aptian), Nuthfield, Surrey Note Associated with fel-pat and pyrite. (X 35)
 B Fuller's Earth (Aptian), Nuthfield, Surrey (X 50)



C, D. APATITE.

- C 1 3 Shore Sand, Co. Dublin (X 65)
 4 9 Trias, Yorkshure. (X 65)
 D Cored Apatite, Trias, Yorkshure (X 59)

Occurrence. In the Northumberland coalfield;¹ in the Lower Argovian limestones and Upper Bajocian, Jura, Switzerland.²

Possible Sources of Derivation. From sedimentary rock masses, either as primary or secondary constituent.

References.

¹ L. Hawkes and J. A. Smythe, *Mineral. Mag.*, 24, 1935, p. 65.

² A. Heim, *Beitr. geol. Karte Schweiz*, 50, 1916.

ANORTHITE

(PLAGIOCLASE FELSPAR GROUP)

Chem. Comp. $\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2$.

System. Triclinic.

Habit. Tabular, prismatic, commonly twinned on Albite law (101); also Pericline law (about b axis) · Carlsbad law (about c axis); Bavono law (021) or Manebach law (001).

Structure. Crystalline.

Cleavage. Perfect || (001), imperfect || (010), rarely || (110). Parting || (100).

Fracture. Irregular.

Hardness. 6.

Spec. Grav. 2.77.

Lustre. Vitreous, pearly.

Colour. White.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low, $\alpha = 1.576$, $\beta = 1.584$, $\gamma = 1.588$. Birefringence moderate, $\gamma - \alpha = 0.012$. Optically biaxial, negative. $2V = 77^\circ$, $2E = 163^\circ$. Oblique extinction. $Bxa = X' \wedge (001) = 37^\circ$, $\wedge (010) = 40^\circ$. Dispersion weak, $\rho > v$.

Characters in Sediments. Detrital anorthite is extremely rare in sediments, being easily altered to "saussurite," a complex mixture of zoisite, epidote, albite, quartz, calcite etc. Diagnosis depends on determination of definite crystal faces presented by grains and on careful measurements of optical properties thereon. The R.I. is higher than Canada balsam, which distinguishes anorthite from albite and oligoclase. Grains inclined to be irregular, generally clear, though with inclusions, e.g. iron ores, zircon. Where twin lamellæ are visible (as is usual) these form broad bands and serve as a useful guide to identity by measurement of extinction angle (37° - 40°) therefrom.

Occurrence. In the soils of Kedivi, Java.¹

Possible Sources of Derivation. Basic and ultrabasic igneous rocks.

Reference.

¹ G. A. Neeb, *Overdruk uit de Handelingen v/h. 7de Ned. Ind. Natuurwetenschappelijk Congres*, 1936, p. 695.

ANORTHOCLEASE

(FELSPAR GROUP)

[Pl. 10 A, B, facing p. 241.]

Chem. Comp. $(\text{Na}, \text{K})_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$.

System. Triclinic.

Habit. Prismatic or tabular || (010). Twinning on Carlsbad, Bavono and Manebach laws. Multiple twinning common.

Structure. Crystalline.

Cleavage. Perfect || (010) and (001).

Fracture. Irregular.

Hardness. 6.

Spec. Grav. 2.58.

Lustre. Vitreous, pearly.

Colour. White.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low, $\alpha = 1.519$, $\beta = 1.525$, $\gamma = 1.527$. Birefringence weak, $\gamma - \alpha = 0.008$. Optically biaxial negative. Optic axial plane \perp (010). Bxa X inclined at 6° to 12° to α in (010). Extinction on (001) 1° to 6° . $2V = 45^\circ$. $2E = 71^\circ$. Dispersion weak, $\rho > \nu$.

Characters in Sediments. In detrital sediments identification of anorthoclase depends largely on grains exhibiting a combination of albite and microcline twinning, in which the former appear as extremely fine, narrow bands. The result is what A. N. Winchell terms a "quadrille structure"—an extremely fine "cross hatching" which is quite distinctive. Alteration to sericite and kaolinite is a common tendency. The very low extinction angle on (001) flakes is characteristic and differs from microcline which is higher (15°). Compound grains intergrown with sanidine (p. 322) may be anticipated.

Occurrence. In the Jurassic Fuller's Earth from Combe Hay, near Bath, Somerset; in the Cretaceous Fuller's Earth of Nutfield, Surrey and Woburn, Bedfordshire (anorthoclase with some amount of lime).¹ Later Tertiary deposits, E. England.²

Possible Sources of Derivation. Soda-bearing volcanic rocks.

REMARKS.—Compare with *microcline*, p. 313, and *orthoclase*, p. 321.

References.

¹ E. F. Newton, *Proc. Geol. Assoc.*, 48, 1937, p. 188 and Pl. 14.

² I. S. Double, *Proc. Geol. Assoc.*, 35, 1924, p. 336.

ANTIGORITE

(CHLORITE GROUP)

Chem. Comp. $3\text{MgO} \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$.

System. Monoclinic or ?Orthorhombic. Pseudoisometric.

Habit. Fibrous; often pseudomorphous.

Structure. Lamellar, massive, fibrous, "net-like."

Cleavage. Pseudoisometric forms with perfect (001), (010) and less perfect (100) cleavages.

Fracture. Irregular, acicular.

Hardness. 4.5.

Spec. Grav. 2.6.

Lustre. Silky.

Colour. Green, greyish yellow.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low, $\alpha = 1.490$, $\beta = 1.502$, $\gamma = 1.511$. Birefringence moderate, $\gamma - \alpha = 0.021$; also $\alpha = 1.560$, $\beta = 1.570$, $\gamma = 1.571$ (A. N. Winchell). Birefringence moderate, $\gamma - \alpha = 0.011$. Optically biaxial, negative. Optic axial plane || (010). Bxa \perp (001). Lamellæ have positive elongation. $Z = b$. $X = c$. Dispersion weak, $\rho > \nu$. Faint pleochroism sometimes noted in thick flakes: $X =$ pale yellow-green, $Y, Z =$ pale green.

Characters in Sediments. Detrital antigorite is extremely variable in appearance in sediments and is difficult of diagnosis unless physical and optical characters are critically determined. Colour, S.G., lamellar character, R.I. and positive elongation of lamellæ serve as a guide, as does the weak pleochroism if developed. May sometimes be confused with chrysotile (p. 267) which tends to a fibrous habit, but the latter is optically positive and has weaker birefringence.

Occurrence. In bore-hole samples from the plain of the River Po, Italy.¹
Possible Sources of Derivation. Ultrabasic igneous rocks (peridotites and serpentines); also as alteration product of olivine, pyroxene, amphibole etc.

REMARKS.—Antigorite *per se* is rarely recorded from detrital sediments, the wider term "serpentine" usually designating an occurrence generally of chrysotile (p. 267), less commonly antigorite. Antigorite is decomposed by HCl, so if anticipated must be searched for in the natural untreated sample. It floats in bromoform unless associated with much iron ore. *Bastite* is a variety of antigorite usually pseudomorphous after rhombic pyroxene (e.g. enstatite, p. 281), but it may also replace diopside (p. 277).

Reference.

¹ I. Chelussi, *Boll. Soc. geol. ital.*, 30, 1911, p. 167.

APATITE [Pl. 10 C, D, facing p. 241.]

Chem. Comp. Fluor - Apatite, $\text{Ca}_4(\text{CaF})(\text{PO}_4)_3$. Chlor - Apatite, $\text{Ca}_4(\text{CaCl})(\text{PO}_4)_3$. Intermediate compounds occur with both F and Cl. Also traces of Mn, Di, Ce, As and Hydroxyl.

System. Hexagonal.

Habit. Prismatic, bipyramidal or with basal pinacoid.

Structure. Usually crystalline, sometimes acicular, massive, granular or compact.

Cleavage. Imperfect $\parallel (0001)$; more rarely $\parallel (10\bar{1}0)$.

Fracture. Uneven, conchoidal.

Hardness. 5. Less in massive varieties (4.5).

Spec. Grav. 3.17-3.23.

Lustre. Vitreous to sub-resinous.

Colour. Commonly white, colourless or shades of green. **Transparent.**

Mag. Prop. Non-magnetic.

Elect. Prop. Weak conductor.

Opt. Prop. R.I. high, $\omega = 1.649$, $\epsilon = 1.644$. Birefringence weak, $\omega - \epsilon = 0.005$. Optically uniaxial, negative. Sometimes exhibits pseudo-biaxial figure with $2E > 10^\circ$. Some coloured varieties weakly pleochroic, $\epsilon > \omega$. Straight extinction. Length fast. Basal sections isotropic.

Characters in Sediments. Rounded elongated prismatic or "egg-shaped" grains most common, sometimes with minute indeterminable inclusions arranged \parallel principal axis: these may be fluid. Grains frequently very small, often showing evidence of solution. Some varieties exhibit dark purple, pleochroic cores or nuclei: see general references, p. 244.

Occurrence. In the Old Red Sandstone, Cardiff area;¹ in certain Palaeozoic rocks of the English Midlands;² in the Devonian rocks of the

Torquay district;³ in the Old Red Sandstone of the West Midlands;⁴ in the Permo-Triassic rocks of the Midlands;⁵ in the Lower Permian rocks of North England;⁶ in the Bunter Pebble Bed, West of England;⁷ in the Upper Lias-Inferior Oolite of the West of England;⁸ in the Cretaceous Fuller's Earth, Surrey;⁹ in the Upper Greensand of the Haldon Hills, Devon;¹⁰ in the Cretaceous Greensand of Farmingdale, New Jersey;¹¹ in the Senonian Stage near Doullens, France;¹² in the Bagshot Beds of Essex;¹³ in the Suffolk Boxstones, England;¹⁴ in the later Tertiary deposits of East England;¹⁵ in the Dartmoor detritals;¹⁶ in the surface deposits of S.E. Devonshire.¹⁷

Possible Sources of Derivation. Igneous rocks, especially granites and syenites.

REMARKS.—Apatite is probably far commoner in sediments than existing records would lead one to believe. It is liable to be lost by solution, either natural or during acid-cleaning of the sediment prior to separation, while its possible confusion with other colourless minerals is not an insignificant factor. The detrital form, R.I., weak birefringence, all serve to differentiate the species, though a confirmatory test for phosphate should always be resorted to where a number of grains occur whose identity as apatite is suspected, but whose diagnosis by microscopical means alone is not positive.

Apatite found in sediments is normally fluorapatite with only a small amount of chlorine; chlorapatite is comparatively rare.

Phosphorite is a natural phosphate and may be regarded as the amorphous, fibrous or concretionary form of apatite. It usually develops from organic remains (animal excreta) interacting with calcite, e.g. coral limestone on desert islands. Recorded by P. G. H. Boswell.¹⁸

References.

- ¹ A. Heard and R. Davies, *Quart. Journ. Geol. Soc.*, 80, 1924, p. 501.
- ² W. F. Fleet, *Geol. Mag.*, 62, 1925, p. 102, 106, 110, 113, 116, 120, 123.
- ³ W. G. Shannon, *Proc. Geol. Assoc.*, 39, 1928, p. 141.
- ⁴ W. F. Fleet, *Geol. Mag.*, 63, 1926, p. 513.
- ⁵ W. F. Fleet, *Proc. Geol. Assoc.*, 38, 1927, p. 1.
- ⁶ H. C. Versey, *Proc. Yorks. Geol. Soc.*, 20, 1925, and *Geol. Mag.*, 61, 1924, p. 380.
- ⁷ H. H. Thomas, *Quart. Journ. Geol. Soc.*, 58, 1902, p. 621.
- ⁸ P. G. H. Boswell, *Geol. Mag.*, 61, 1924, p. 257.
- ⁹ E. F. Newton, *Proc. Geol. Assoc.*, 48, 1937, p. 180 and Pl. 15.
- ¹⁰ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 79, 1923, p. 226.
- ¹¹ S. J. Diller, *U.S. Geol. Surv., Bull.* 150, 1898, p. 1.
- ¹² H. Lasne, *Bull. Soc. géol. France*, 18, *Series* 3, 1890, p. 441.
- ¹³ S. W. Wooldridge, *Proc. Geol. Assoc.*, 35, 1924, p. 359.
- ¹⁴ P. G. H. Boswell, *Geol. Mag.*, 1915, p. 250.
- ¹⁵ I. S. Double, *Proc. Geol. Assoc.*, 35, 1924, p. 338.
- ¹⁶ A. Brammall, *Proc. Geol. Assoc.*, 39, 1928, p. 39.
- ¹⁷ W. G. Shannon, *Geol. Mag.*, 64, 1927, p. 147.
- ¹⁸ P. G. H. Boswell, *Proc. Liverpool Geol. Soc.*, 13, 1923, p. 268.

General References.

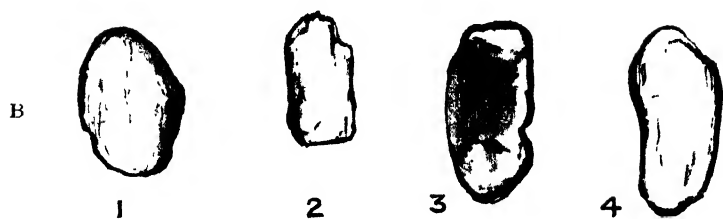
- W. Mackie, "The Apatites in Sedimentary Rocks as Indicators of the Amount of Atmospheric Carbonic Acid in the Periods of Deposit." *Trans. Geol. Soc. Glasgow*, 17, 1926, p. 407.
- W. F. Fleet and F. Smithson, "On the Occurrence of Dark Apatite in some British Rocks." *Geol. Mag.*, 65, 1928, p. 6.
- A. W. Groves and A. E. Mourant, "Inclusions in the Apatites of some Igneous Rocks." *Mineral. Mag.*, 22, 1929, p. 92.
- B. Simpson, "The Dusky Apatites of the Eskdale (Cumberland) Granite." *Geol. Mag.*, 70, 1933, p. 375.



A

A. ARAGONITE

Shell fragments, Shore Sand, Aberdeenshire [x 2]



B

1

2

3

4



B, C. AUGIF.

- B 1, 2 Recent Sands, Rosslare, Co. Wexford [x 70]
 3 Recent Sands, Cape Verde Is. [x 70]
 4 Blown Sands, Newgale, Pembroke-shire [x 70]
 C. River Sand, Tyrol [x 70]

ARAGONITE [Pl. 11 A, facing p. 245.]

Chem. Comp. CaCO_3 .

System. Orthorhombic.

Habit. Euhedral, acicular and as interpenetration twins resulting in pseudo-hexagonal "platy" forms.

Structure. Crystalline, globular, earthy.

Cleavage. Good $\parallel (010)$; imperfect $\parallel (110)$ and (011) .

Fracture. Subconchoidal.

Hardness. 3.5-4.

Spec. Grav. 2.93-2.95.

Lustre. Vitreous, resinous on fractured surfaces.

Colour. Colourless, grey, greyish-yellow, green, mauve.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. both lower and higher than Canada balsam, as in calcite, $\alpha=1.530$, $\beta=1.680$, $\gamma=1.685$. Birefringence very strong, $\gamma-\alpha=0.155$. Optically biaxial, negative. Optical axial plane $\parallel (100)$. $Bxa=X \parallel c$, $\perp (001)$; $Z \parallel b$. Length fast. Optic axial angle small, $2V=18^\circ$, $2E=30^\circ$. Weak dispersion, $\rho < v$. Straight extinction in prismatic grains. Non-pleochroic. Characteristic "twinkling" as in calcite.

Characters in Sediments. Detrital aragonite is extremely rare and the irregularly-shaped fragments met with in certain sediments are usually ascribable to broken lamellibranch shells or possibly gastropod remains. The porcellaneous forms of *foraminifera* are mainly of aragonite. Otherwise it is difficult to be certain of definite diagnosis of this mineral by microscopical means alone and chemical tests are desirable if possible, chiefly to distinguish it from calcite.

Occurrence. In certain typical sediments from the Upper Cretaceous of Maryland, U.S.A.;¹ in the North Sea Drift and Upper Glacial Brick-earths of East Anglia;² in the modern Fenland Silt on the north-west coast of the Wash, near Friskney;³ in the mud-deposits of the "limans" of Kuyabuk, near Odessa, Russia;⁴ as fragments of probable organic origin in many Tertiary and Recent deposits, e.g. Pliocene of Walton-on-Naze, Essex.⁵

Possible Sources of Derivation. Where not of organic origin almost certainly authigenic and associated with limestone and gypsum; also occurs in vesicles in basalts and various lavas to which it may be locally traced in some instances.

REMARKS.—Aragonite is distinguished from calcite by its higher S.G. and absence of rhombohedral cleavage; also by Meigen's reaction:—boil grains with $\text{Co}(\text{NO}_3)_2$ when a lilac or violet colour quickly appears. Another test is to treat the $\text{Co}(\text{NO}_3)_2$ stained grains with ammonium sulphide solution, when cobalt sulphide is precipitated on the aragonite grains more thickly than on any associated calcite grains, resulting in dense black aggregates on the former species.

References.

¹ M. I. Goldman, *Maryland Geol. Surv.*, 1916, p. 111.

² P. G. H. Boswell, *Proc. Geol. Assoc.*, 27, 1916, p. 79.

³ F. Hardy, *Geol. Mag.*, 57, 1920, p. 543.

⁴ M. Sidorenko, *Zap. novoruss. obschch. vestestvoisp.*, 21, 1897, p. 118.

⁵ Author's observations.

ARFVEDSONITE

(AMPHIBOLE GROUP)

Chem. Comp. $5\text{Na}_2\text{O} \cdot 2\text{CaO} \cdot 14\text{MgO} \cdot 3\text{Al}_2\text{O}_3 \cdot 30\text{SiO}_2 \cdot 2\text{TiO}_2 \cdot 2\text{H}_2\text{O}$.*System.* Monoclinic.*Habit.* Long prisms or "blades" || c.*Structure.* Crystalline, fibrous.*Cleavage.* Perfect || (110) at 124° *Fracture.* Irregular.*Hardness.* 6.*Spec. Grav.* 3.33-3.45.*Lustre.* Vitreous.*Colour.* Blue, black.*Mag. Prop.* Moderately magnetic.*Elect. Prop.* Poor conductor.

Opt. Prop. R.I. high, $\alpha = 1.670$, $\beta = 1.680$, $\gamma = 1.682$. Birefringence moderate, $\gamma - \alpha = 0.012$. Optically biaxial, negative. Optic axial plane and $Z \perp (010)$. Elongation of prism negative. Extinction angle $X \wedge c = 14^\circ$ to $+20^\circ$; $Z \wedge c = 20^\circ - 25^\circ$. $Y = b$. Optic axial angle variable about X . Pleochroism strong, $X = \text{dark green}$ $> Y = \text{pale brown}$ $> Z = \text{black}$. Strong dispersion.

Characters in Sediments. Detrital arfvedsonite is characterised by its tendency to occur in blue or bluish green fibrous or prismatic grains, having distinctive pleochroism and relatively high extinction angle compared with hornblende, actinolite or riebeckite; also such extinction is generally incomplete owing to strong dispersion of bisectrices. Incipient or nearly complete alteration to siderite and limonite may be noted.

Occurrence. In the North Sea Drift and Upper-Glacial Brick-Earths of East Anglia;¹ in surface deposits, gravels of present and ancient river systems and plateau gravels of Cambridgeshire;² in the modern Fenland Silt of the north-west coast of the Wash, near Friskney;³ in the sands on the south shore of Long Island and the coast of New Jersey;⁴ in association with dolomite in a trench cut at Fulford, East Yorkshire.⁵

Possible Sources of Derivation. Soda-bearing igneous rocks, e.g. nepheline-syenite.

References.

- ¹ P. G. H. Boswell, *Proc. Geol. Assoc.*, 27, 1916, p. 79.
- ² R. H. Rastall, *Proc. Cambridge Phil. Soc.*, 17, 1913, p. 132.
- ³ F. Hardy, *Geol. Mag.*, 57, 1920, p. 543.
- ⁴ R. J. Colony, *Journ. Sed. Pet.*, 2, 1932, p. 150.
- ⁵ S. Melmore, *Naturalist*, 1929, p. 341.

AUGITE

[Pl. 11 B, C, facing p. 245.]

(PYROXENE GROUP)

Chem. Comp. $\text{CaO} \cdot 2(\text{Mg}, \text{Fe})\text{O} \cdot (\text{Al}, \text{Fe})_2\text{O}_3 \cdot 3\text{SiO}_2$. Also titaniferous varieties.

System. Monoclinic.

Habit. Commonly prismatic with varying terminations; twinning on (100) common.

Structure. Usually crystalline, sometimes granular.

Cleavage. Good || (110), more rarely || (100). (001) parting frequently observed given by twin lamellæ || (100).

Fracture. Uneven.

Hardness. 5-6.

Spec. Grav. 3.2-3.6 (varies with composition).

Lustre. Vitreous, sometimes resinous.

Colour. Shades of yellowish-green, green to blackish-green. Sometimes brown.

Mag. Prop. Moderately magnetic; varies with the amount of iron present.

Elect. Prop. Moderately good conductor.

Opt. Prop. R.I. very high, $\alpha=1.699$, $\beta=1.718$, $\gamma=1.742$. Birefringence strong, $\gamma-\alpha=0.043$. Optically biaxial, positive. Optic axial plane $\parallel (010)$. $Y \parallel b$. $Bxa = Z \wedge c = 46^\circ-51^\circ$: oblique extinction $2V=65^\circ$.¹ Slightly pleochroic in some titaniferous varieties with characteristic violet or red tint (Y). Dispersion $\rho > v$.

Characters in Sediments. Grains usually either rounded prismatic forms or irregular cleavage fragments, the latter often showing the emergence of an optic axis. Fractured or "broken" grains are sometimes met with which are very characteristic of the particular horizon at which they occur. Diagnosed chiefly by its colour and high extinction angle and anticipated where other pyroxenes, also olivine, are prevalent.

Occurrence. In the Silurian rocks of Southern Scotland;¹ in the Lower Old Red Sandstone of the Forfarshire Coast;² in the Old Red Sandstone of the West Midlands;³ in the Senonian Coal-Measure clays of the Malvern Hills, New Zealand;⁴ in the Permo-Triassic rocks of the Midlands;⁵ in certain Boulder Clays of Yorkshire;⁶ in surface and plateau gravels, Cambridgeshire;⁷ in surface deposits of S.E. Devonshire;⁸ in the deep sea deposits of the Atlantic Ocean;⁹ in the dune sands of South Wales;¹⁰ in shore sands at Rosslare, Co. Wexford;¹¹ in shore sands of Cape Verde Islands;¹² in blown sand at Newgale, Pembrokeshire;¹³ in the sands of the Northumberland coast.¹⁴

Possible Sources of Derivation. Intermediate and basic igneous rocks.

REMARKS.—As would be expected, augite is somewhat haphazard in its occurrence in sediments, though it is frequently very common in deep-sea deposits and shore sands fed by disintegrated volcanic materials. Sometimes it is difficult to decide between augite and diopside in diagnosis; there is much to be said for restricting the latter label to the pale green or colourless grains found in pyroxene-rich samples the striking feature of which is often their surprising freshness, in contrast to the yellower-green augite which frequently exhibits traces of decomposition or dusky inclusions of iron-ores. See also diopside, p. 277, and ægirine, p. 230. †Varies, as with other optical properties, with the amount of Al_2O_3 and Fe_2O_3 present.

References.

- ¹ W. Mackie, *Rep. Brit. Assoc.*, 1928 (*Glasgow*), 1929, p. 556
- ² A. Jowett, *Quart. Journ. Geol. Soc.*, 69, 1913, p. 459.
- ³ W. F. Fleet, *Geol. Mag.*, 63, 1926, p. 513.
- ⁴ S. Page, in R. Speight, *Geol. Mem. Dept. Sci. and Ind. Research*, New Zealand, 1, 1928, p. 1.
- ⁵ W. F. Fleet, *Proc. Geol. Assoc.*, 38, 1927, p. 6.
- ⁶ A. Raistrick, *Geol. Mag.*, 66, 1929, p. 337.
- ⁷ R. H. Rastall, *Proc. Cambridge Phil. Soc.*, 17, 1913, p. 132.
- ⁸ W. G. Shannon, *Geol. Mag.*, 64, 1927, p. 147.
- ⁹ J. Murray and J. Chumley, *Trans. Roy. Soc. Edinburgh*, 54, 1924, p. 1.
- ¹⁰ A. Stuart, *Proc. Geol. Assoc.*, 35, 1924, p. 323.
- ¹¹ Author's observations.
- ¹² Noted by G. M. Part.
- ¹³ Author's observations.
- ¹⁴ L. Hawkes and J. A. Smythe, *Geol. Mag.*, 68, 1931, p. 345.

AXINITE

[Pl. 12 A, facing p. 252.]

Chem. Comp. $6(\text{Ca}, \text{Fe}, \text{Mn})\text{O} \cdot 2\text{Al}_2\text{O}_3 \cdot \text{B}_2\text{O}_3 \cdot 8\text{SiO}_2 \cdot \text{H}_2\text{O}$.*System.* Triclinic.*Habit.* Diamond- or wedge-shaped crystals, sometimes euhedral, rarely prismatic; flattened.*Structure.* Crystalline, rarely lamellar or granular.*Cleavage.* Distinct $\parallel (010)$; sometimes $\parallel (001)$ and $(1\bar{3}0)$.*Fracture.* Conchoidal.*Hardness.* 6.5-7.*Spec. Grav.* 3.25-3.30.*Lustre.* Vitreous.*Colour.* Pinkish-brown to red, "plum," greyish-yellow; shades of mauve and yellowish-red; rarely colourless.*Mag. Prop.* Non-magnetic.*Elect. Prop.* Poor conductor.*Opt. Prop.* R.I. high, $\alpha = 1.678$, $\beta = 1.685$, $\gamma = 1.688$. Birefringence moderate, $\gamma - \alpha = 0.010$. Optically biaxial, negative. Trace of optic axial plane inclined 40° to edge $(111)(1\bar{1}0)$ and $24^\circ 40'$ to $(111)(1\bar{1}\bar{1})$, (A. Des Cloizeaux). $Bxa = X$ practically $\perp (111)$. Oblique extinction $(111) \wedge (110) = 40^\circ$. $(111) \wedge (1\bar{1}\bar{1}) = 24^\circ$. $2V = 71^\circ 38'$ (red). Strong dispersion, $\rho < \nu$. Pleochroism moderate: X = pale green, olive green, Y = dark blue or violet, Z = brown; only observed in thick grains.*Characters in Sediments.* Occurs in irregular or rounded, diamond-shaped grains of characteristic colour, usually a delicate shade of mauve or pink. The grains reveal the presence of small conchoidal fractures, which are characteristic. Detrital axinite is for the most part non-pleochroic unless the grains are large. Grains frequently fail to extinguish in any position.*Occurrence.* Observed only in Recent Sands, in particular the shore sands at various points along the Land's End—St. Ives coast, Cornwall.¹*Possible Sources of Derivation.* Metamorphosed basic igneous rocks (pneumatolytic modifications); cavities in granitic rocks.**REMARKS.**—A local species to be anticipated in recent sediments rather than in those of greater age. Often associated with pyroxene, amphibole, calcite and sulphide ores.*Reference.*¹ Author's observations.**BARITE**

[Pl. 12 B, C, facing p. 252.]

Chem. Comp. BaSO_4 .*System.* Orthorhombic*Habit.* Prismatic, with basal plane strongly developed. Twinning on (100) common.*Structure.* Crystalline, massive or lamellar.*Cleavage.* Perfect $\parallel (001)$ and (110) ; imperfect $\parallel (010)$.*Fracture.* Uneven.*Hardness.* 3.*Spec. Grav.* 4.5.*Lustre.* Vitreous, pearly, often combined with "cloudy" appearance.*Colour.* Colourless, bluish-white or yellow. Transparent to translucent.*Mag. Prop.* Non-magnetic.*Elect. Prop.* Bad conductor.

Opt. Prop. R.I. high, $\alpha=1.636$, $\beta=1.637$, $\gamma=1.648$. Birefringence moderate, $\gamma-\alpha=0.012$. Optically biaxial, positive. Optic axial plane \parallel (010). Length slow. $Bxa=Z \perp (100)$. $2V=37^\circ 30'$. $X \parallel c$, $Y \parallel b$, $Z \parallel a$. Prismatic grains give straight extinction. Cleavage grains may show emergence of the bxo . Dispersion weak, $\rho < v$.

Characters in Sediments. Fragments of this mineral are varied in character; the normal type is entirely irregular, angular and determined chiefly by fracture, cleavage or the original shape of the interstice which it filled as a cementing medium. Sharply angular cleavage fragments are common, but seldom yield good interference figure. Grains rarely show rounding, though they may be intensely fractured. Diagnosed chiefly by its high S.G. and optical properties, also by its "patchy" lustre, brown staining and varied inclusions (iron-ores).

Occurrence. In the Cambrian, Ordovician, Silurian, Devonian, Carboniferous, Permian and Triassic rocks of the English Midlands;¹ in the Ordovician rocks of Carnarvonshire;² in the Old Red Sandstone of the West Midlands;³ in the Old Red Sandstone of the Cardiff district;⁴ in the Lower Carboniferous sandstones of West Cumberland;⁵ in the Millstone Grit of Yorkshire;⁶ in the Coal-Measure Clay, Seaton, Northumberland;⁷ in the Permo-Triassic rocks of the Midlands;⁸ in the Lower-Permian rocks of Northern England;⁹ in all areas where sandstones of Triassic age occur, e.g. Cheshire, Staffordshire, Nottinghamshire, Devonshire etc.;¹⁰ in the Keuper Marls around Charnwood;¹¹ in the New Red Sandstone of West England;¹² in the New Red Rocks of the Quantock Hills;¹³ in the Fuller's Earth and Folkestone Beds (Lower Greensand) of Surrey and Kent respectively;¹⁴ in the Lower London Clay at Sheppey;¹⁵ in the river sand from the Ure and Ouse;¹⁶ in shore sands from Co. Cork, Eire;¹⁷ in the sands of the Northumberland Coast.¹⁸

Possible Sources of Derivation. From sandstones in which it acts as the cementing medium; from veins in limestones associated with calcite; from the gangue of metalliferous veins or from massive deposits of barite associated with calcareous sediments.

REMARKS.—Rarely met with as detrital grains; H. C. Versey has described both authigenic and allogenic occurrences; presence in residue usually due to the disintegration of the cementing medium of a sand on treatment of the latter for "heavy" mineral analysis. Distinguish from anhydrite by the forms and cleavages of that mineral. Barite has the higher S.G. and the characteristic lustre noted above.

References.

- ¹ W. F. Fleet, *Geol. Mag.*, 62, 1925, p. 98.
- ² S. A. Billingham, *Geol. Mag.*, 66, 1929, p. 289.
- ³ W. F. Fleet, *Geol. Mag.*, 63, 1926, p. 512.
- ⁴ A. Heard and R. Davies, *Quart. Journ. Geol. Soc.*, 80, 1924, p. 489.
- ⁵ H. P. Lewis, *Geol. Mag.*, 68, 1931, p. 543.
- ⁶ A. Gilligan, *Quart. Journ. Geol. Soc.*, 75, 1919, p. 251.
- ⁷ W. M. Hutchings, *Geol. Mag.*, 1890, p. 264, 316.
- ⁸ W. F. Fleet, *Proc. Geol. Assoc.*, 38, 1927, p. 6.
- ⁹ H. C. Versey, *Proc. Yorks. Geol. Soc.*, 20, 1925, p. 200.
- ¹⁰ H. W. Greenwood, *Proc. Liverpool Geol. Soc.*, 12, 1920, p. 355.
- ¹¹ T. O. Bosworth, *Quart. Journ. Geol. Soc.*, 68, 1912, p. 281.
- ¹² H. H. Thomas, *Quart. Journ. Geol. Soc.*, 65, 1909, p. 234.
- ¹³ H. H. Thomas, *Mem. Geol. Surv.*, Great Britain Sheet 295, 1908, p. 60.
- ^{14, 15} G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915-16, p. 93.
- ¹⁶ S. Melmore, *Geol. Mag.*, 63, 1926, p. 268.
- ¹⁷ Author's observations.
- ¹⁸ L. Hawkes and J. A. Smythe, *Geol. Mag.*, 68, 1931, p. 345.

General Reference.

- J. M. Sweet, "Notes on British Barytes." *Mineral Mag.*, 22, 1930, p. 357.

BARKEVICITE

(AMPHIBOLE GROUP)

Chem. Comp. Between hornblende (p. 297) and arfvedsonite (p. 246): variety of hornblende rich in Fe^{II} and alkalis.

System. Monoclinic.

Habit. Prismatic, fibrous.

Structure. Crystalline.

Cleavage. Perfect || (110).

Fracture. Irregular.

Hardness. 6.

Spec. Grav. 3.43.

Lustre. Vitreous.

Colour. Green, greenish brown to black.

Mag. Prop. Moderately magnetic.

Elect. Prop. Moderate conductor.

Opt. Prop. R.I. high, $\alpha = 1.687$, $\beta = 1.707$, $\gamma = 1.708$. Birefringence moderate, $\gamma - \alpha = 0.021$. Optically biaxial, negative. Oblique extinction, $Z\wedge c = 12^\circ$ to 14° . $X = b$. Length slow. $2V = 54^\circ$. $2E = 102^\circ$. Pleochroism distinctive: $X =$ brown yellow $> Y =$ reddish brown $> Z =$ deep brown.

Characters in Sediments. Prismatic or irregular (010) grains determined by cleavage, having distinctive green colour and pleochroism. Differs from hornblende chiefly in pleochroism and generally smaller extinction angle; from arfvedsonite in pleochroism and larger extinction angle of that species.

Occurrence. In the Dune Sands of South Wales.¹

Possible Sources of Derivation. Alkaline intermediate igneous rocks, e.g. nepheline-syenite.

Reference.

¹ A. Stuart, *Proc. Geol. Assoc.*, 35, 1924, p. 331. *Proc. Swansea Sci. and Field Nat. Soc.*, 1, 1927, p. 16.

BASALTINE. Basaltic Hornblende

(AMPHIBOLE GROUP)

Chem. Comp. $3CaO \cdot Na_2O \cdot 7(Mg, Fe)O \cdot 3(Al, Fe)_2O_3 \cdot TiO_2 \cdot 12SiO_2 \cdot 2H_2O$.

System. Monoclinic.

Habit. Prismatic || c. Lamellar twinning about (100).

Structure. Crystalline, massive.

Cleavage. Perfect || (110). Less distinct || (100) and (010). Cleavage traces in cross sections \perp prism zone intersect at 124° . Parting in twin crystals || (100) and (010).

Fracture. Uneven, subconchoidal.

Hardness. 6.

Spec. Grav. 3.18.

Lustre. Vitreous.

Colour. Brown to black.

Mag. Prop. Moderately magnetic.

Elect. Prop. Moderate conductor.

Opt. Prop. R.I. high, $\alpha = 1.670$, $\beta = 1.683$, $\gamma = 1.693$. Birefringence moderate, $\gamma - \alpha = 0.023$. Optically biaxial, negative. Optic axial plane || (010). Length and cleavage trace slow. $Y = b$. Oblique extinction. $Z\wedge c = 9^\circ$, smaller in many examples ($1^\circ - 2^\circ$). $Bxa = X$ in

clined at low angle to \perp of (100). $2V=83^\circ$. Dispersion small, $\rho > v$. Pleochroism variable: $Z=\text{dark olive green or brown} > Y=\text{dark brown} > X=\text{pale yellow}$.

Characters in Sediments. Basaltine occurs in sediments in similar form of grains to ordinary hornblende. It is identified by colour, usually brownish yellow, deep brown or almost opaque, prismatic cleavage, very low extinction angle (almost straight in many examples), and distinctive pleochroism. Basaltine has a higher specific gravity and R.I. than common hornblende. Inclusions generally iron ores, sometimes magnetite; also zircon, apatite and glass. Grains are usually fresh, showing little tendency to decomposition products.

Occurrence. In Eocene Sandstones etc., of West Central Italy;¹ in the Pleistocene-Recent deposits of the Lazard area, San Joaquin Valley, California;² in the Limburg Loess;³ in the Mediterranean deep sea deposits;⁴ in the soils of Java;⁵ in sands of the Kettleman Hills, California, U.S.A.⁶

Possible Sources of Derivation. Volcanic lavas.

REMARKS.—Formed essentially by the oxidation of the iron in ordinary hornblende, hence the synonym "oxyhornblende."

References.

- ¹ L. Maddalena, *C.R. Intern. Géol. Congr.*, 13th Session, 1922, iii (1926), p. 1309.
- ² R. D. Reed and J. P. Bailey, *Bull. Amer. Assoc., Petrol. Geol.*, 11, 1927, p. 363.
- ³ J. H. Druif, "Over het ontstaan der Limburgsche Löss in verband met Haar mineralogische samenstelling," 1927, *Utrecht*.
- ⁴ I. Chelussi, *Boll. Soc. geol. ital.*, 31, 1912, p. 79.
- ⁵ H. Loos, "Bijdrage tot de kennis van eenige bodem soorten van Java en Sumatra." *Wageningen*, 1924.
- ⁶ M. N. Bramlette, *Bull. Amer. Assoc. Petrol. Geol.*, 18, 1934, p. 1559.

BASTITE

See Antigorite, p. 242, Diopside, p. 277, and Enstatite, p. 281.

BEIDELLITE

(MONTMORILLONITE-BEIDELLITE SERIES)

Chem. Comp. $\text{Al}_2\text{O}_3 \cdot 3\text{SiO}_2 \cdot n\text{H}_2\text{O}$.

System. ?Orthorhombic.

Habit. Laminated.

Structure. Crystalline.

Cleavage. Perfect || (001).

Fracture. ?

Hardness. Soft.

Spec. Grav. 2.58—2.62

Lustre. Pearly.

Colour. Colourless.

Mag. Prop. ?

Elect. Prop. ?

Opt. Prop. R.I. low, $\alpha = 1.495$, $\beta = 1.537$, $\gamma = 1.537$. Birefringence strong, $\gamma - \alpha = 0.042$. Optically biaxial, negative. $X = c$. Optic axial angle small.

Characters in Sediments. Occurs in flat platy or laminated grains, resembling mica. Usually these plates yield a good biaxial negative interference figure.

Occurrence. In the underclays of Illinois Coal, U.S.A.¹

Possible Sources of Derivation. Clays; bentonite.

REMARKS.—Beidellite is a member of a series of hydrated aluminous silicates characteristic of certain finely divided sediments such as clays. This series includes *montmorillonite* (p. 315), *nontronite* (p. 318), *rillonite* etc.

Reference.

¹ V. T. Allen, *Journ. Amer. Ceram. Soc.*, 15, 1932, p. 564.

General References.

C. S. Ross and E. V. Shannon, "The chemical composition and optical properties of Beidellite." *Journ. Washington Acad. Sci.*, 15, 1925, p. 467.

C. S. Ross and E. V. Shannon, "The Minerals of Bentonite and related clays and their physical properties." *Journ. Amer. Ceram. Soc.*, 9, 1926, p. 77.

BENITOITE

Chem. Comp. $\text{BaO} \cdot \text{TiO}_2 \cdot 3\text{SiO}_2$.

System. Trigonal.

Habit. Pyramidal, tabular

Structure. Crystalline.

Cleavage. Imperfect $\parallel (10\bar{1}1)$.

Fracture. Irregular.

Hardness. 6.

Spec. Grav. 3.65.

Lustre. Vitreous.

Colour. Blue, purple, sometimes colourless; liable to vary in same crystal.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. very high, $\epsilon = 1.804$, $\omega = 1.757$. Birefringence strong, $\epsilon - \omega = 0.047$. Optically uniaxial, positive. Length slow. Straight extinction. Pleochroism distinctive: $\omega =$ colourless, $\epsilon =$ purple, indigo or greenish-blue.

Characters in Sediments. Benitoite is an extremely rare and local mineral, described from sediments in the San Benito River (head waters) area, California, U.S.A. It occurs in distinctive blue grains having characteristic optical properties (as above), especially marked blue or greenish blue to colourless pleochroism.

Occurrence. In the Upper Famennian Sandstone of the Devonian of the valley of the Ourthe, Belgium;¹ in the Carrizo sand of South-West Texas.²

Possible Sources of Derivation. Schist, serpentine, in which it occurs as veins or in geodes.

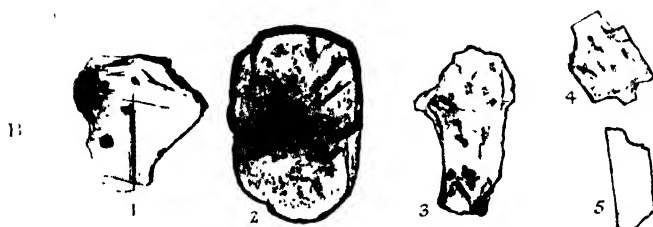
¹ J. Anten, *Ann. Soc. géol. Belg.*, Liège, 51, 1928, p. B. 330.

² J. J. Lonsdale, M. S. Metz and M. T. Halbouty, *Journ. Sed. Pet.*, 1, 1931, p. 73.



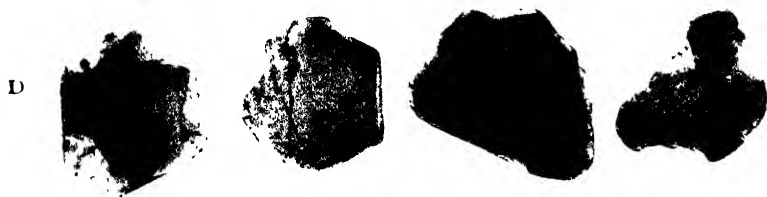
A. AXINITE.

(3) Shore Sand, near Carrick Du, St. Ives, Cornwall [X 40]



B. C. BARITE.

B (1-3) Shore Sand, Co. Cork, I. S. [X 20]
 (4-5) Kruper Sand, Alderley Edge, Cheshire [X 35]
 C River Sand, R. Eden, Cumberland [X 22]



D. BIOTITE.

Shore Sand, Dinard, Brittany [X 23]

BIOTITE [Pl. 12 D, facing p. 252.]

(MICA GROUP)

Chem. Comp. $K_2O \cdot 4(Fe, Mg)O \cdot 2(Al, Fe)_2O_3 \cdot 6SiO_2 \cdot H_2O$.**System.** Monoclinic.**Habit.** Tabular; short, almost hexagonal, prismatic crystals with well-developed basal planes. Frequently twinned on (110) in thin (001) laminæ.**Structure.** Irregular, but strongly laminated. Crystals rare.**Cleavage.** Perfect basal (001). Parting || (010) and (111).**Fracture.** Uneven.**Hardness.** 2.5-3.**Spec. Grav.** 2.79-3.16.**Lustre.** Vitreous, resinous or dull.**Colour.** Dark-green, brown to blackish-brown.**Mag. Prop.** Moderately magnetic.**Elect. Prop.** Moderate conductor.**Opt. Prop.** R.I. low, $\alpha = 1.584$, $\beta = 1.648$, $\gamma = 1.648$. Birefringence strong, $\gamma - \alpha = 0.064$. Optically biaxial, negative. $Bxa = X \perp (001)$; optic axial angle small in certain varieties, giving pseudo-uniaxial interference figure. $X \wedge c$ small. $Y = b$. Pleochroism varies with composition, being strongest in the deep brown facies (phlogopite): $X = \text{colourless}$ $< Y = Z = \text{brownish yellow}$.**Characters in Sediments.** Occurs mostly as brown or yellow cleavage flakes with jagged edges; seldom worn. Pleochroic halos round crystals of zircon, xenotime, allanite etc., enclosed in biotite are of frequent occurrence, especially in the deep brown varieties; other inclusions noted are rutile, anatase and monazite. Striations common. Detrital flakes tend to lie with (001) in the plane of the slide, hence are non-pleochroic. Partial alteration to chloritic matter, producing a "bleached" grain, is commonly observed. Diagnosed almost invariably by its colour, cleavage and almost uniaxial negative interference figure yielded by (001) flakes.**Occurrence.** In the Devonian rocks of the Torquay district;¹ in the Grindstones from the Coal Measures, Yorkshire;² in the Upper Lias—Lower Inferior Oolite sands of West England;³ in Bentonite (Cretaceous) of Wyoming, U.S.A.;⁴ in the Pliocene deposits of Cornwall;⁵ phlogopite in Cornish Pliocene;⁶ in the later Tertiary deposits of East England;⁷ in dune sands of South Wales;⁸ in Dartmoor detritals;⁹ in Chalk boulders from the seafloor off the Scottish coast;¹⁰ in shore sands from Dinard, Brittany and from White Sand Bay, Cornwall;¹¹ in marine peat, Union Dock, Liverpool.¹²**Possible Sources of Derivation.** Igneous and metamorphic rocks.**References.**

- ¹ W. G. Shannon, *Proc. Geol. Assoc.*, 39, 1928, p. 141.
- ² H. P. Lewis and W. J. Rees, *Geol. Mag.*, 63, 1926, p. 13.
- ³ P. G. H. Boswell, *Geol. Mag.*, 61, 1924, p. 257.
- ⁴ D. F. Hewett, *U.S. Geol. Surv. Proj. Paper* 145, 1926, p. 1.
- ⁵ H. B. Milner, *Quart. Journ. Geol. Soc.*, 78, 1922, p. 364.
- ⁶ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 79, 1923, p. 226.
- ⁷ I. S. Double, *Proc. Geol. Assoc.*, 35, 1924, p. 341, 343.
- ⁸ A. Stuart, *Proc. Geol. Assoc.*, 35, 1924, p. 323.
- ⁹ A. Brammall, *Proc. Geol. Assoc.*, 39, 1928, p. 46.
- ¹⁰ H. H. Thomas in W. Hill, *Proc. Roy. Soc. Edinburgh*, 35, 1915, p. 263.
- ¹¹ Author's observations.
- ¹² J. Lomas, *Rep. Brit. Assoc.*, 1907 (Leicester), 1908, p. 516.

BRONZITE(VARIETY OF ENSTATITE. *q.v.* p. 281)**BROOKITE**

[Pl. 13, facing p. 256.]

Chem. Comp. TiO_2 .*System.* Orthorhombic.*Habit.* Prismatic, tabular, $\parallel(100)$, $\parallel(001)$ or pyramidal. Often striated \parallel principal axis.*Structure.* Crystalline.*Cleavage.* Poor $\parallel(110)$ and (001) .*Fracture.* Subconchoidal, irregular.*Hardness.* 5.5-6.*Spec. Grav.* 3.87-4.08.*Lustre.* Resinous, vitreous, submetallic.*Colour.* Shades of brown and yellow. Translucent.*Mag. Prop.* Non-magnetic.*Elect. Prop.* Moderate conductor.

Opt. Prop. R.I. very high, $\alpha=2.583$, $\beta=2.586$, $\gamma=2.741$. Birefringence very strong, $\gamma-\alpha=0.158$. Optically biaxial, positive. $Bxa=Z \parallel a$, $\perp(100)$. Optical properties are anomalous; optic axial plane $\parallel(001)$ for red and yellow light and $\parallel(010)$ for green and blue light; *i.e.* $Xr \parallel b$, or $Xb \parallel c$. For intermediate colour (yellow-green) brookite is uniaxial and isotropic. Optic axial angle varies: for red light $2E=55^\circ$, for yellow $2V=30^\circ$, for green $2E=34^\circ$, for yellow-green $2E=0^\circ$. $Z>Y>X$, or $Y>Z>X$. Non-pleochroic as a rule, but (001) grains are pleochroic. Many crystals fail to extinguish in any position; some show straight extinction \parallel principal striæ or prism-edge. Dispersion very strong. For a full and illustrated discussion on the optical properties of detrital brookite, see reference ¹¹, p. 255, and Note, p. 255.

Characters in Sediments. Detrital brookite is a somewhat elusive species. Normally occurs as dusky brown or yellow grains, tabular $\parallel(100)$, while (110) and (010) types are observed. Noteworthy absence of extinction; interference colour change on rotation. Striæ \parallel principal axis are common, also noted by A. Brammall \parallel b-axis. Inclusions are commonly detected, these being "aggregates and stringers of opaque dust," also in the Dartmoor types, rutile, tourmaline, rarely topaz and globular isotropic bodies.

Occurrence. In the Cambrian Quartzites of Shankill, Ireland;¹ in the Bunter Pebble Bed of the West of England;² in the New Red Sandstone of the West of England;³ in the Jurassic sandstones of Eskdale, Yorkshire;⁴ in the Cleveland Ironstone;⁵ in the Upper Lias—Lower Inferior Oolite sands of the West of England;⁶ in the Greensand of the Haldon Hills, Devonshire;⁷ in the Oligocene beds of the Bovey Basin, Devonshire;⁸ in the Pliocene deposits of West Cornwall;⁹ in the later Tertiary deposits (Red Crag, Chillesford Beds etc.) of East England;¹⁰ in Dartmoor detritals.¹¹

Possible Sources of Derivation. Acid igneous and crystalline metamorphic rocks; from the pneumatolysis and tourmalinisation of titaniferous biotite. See A. Brammall, *op. cit.* p. 47, also this volume, under ilmenite, p. 301. When abundant probably authigenic.

REMARKS.—Students of the titanium minerals in sediments owe much to A. Brammall and H. F. Harwood for their exhaustive studies of these species, particularly brookite which has always presented certain difficulties in unequivocal diagnosis. In the paper on "Dartmoor Detritals,"¹¹ the former author gives much information applicable to the identification of brookite under all conditions, together with some good illustrations of the Dartmoor types and their curious interference figures, the latter here reproduced in *Fig. 78*, p. 256.

References.

- ¹ J. P. O'Reilly, *Sci. Proc. Roy. Dublin Soc.*, 8, 1898, p. 732.
- ² H. H. Thomas, *Quart. Journ. Geol. Soc.*, 58, 1902, p. 625, *Pl. 32, Fig. 6*
- ³ H. H. Thomas, *Quart. Journ. Geol. Soc.*, 65, 1909, p. 238.
- ⁴ R. H. Rastall, *Proc. Yorks. Geol. Soc.*, 22, 1932, p. 93.
- ⁵ J. E. Stead, *Proc. Cleveland Inst. Eng., Middlesbrough*, 1910, p. 75.
- ⁶ P. G. H. Boswell, *Geol. Mag.*, 61, 1924, p. 257.
- ⁷ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 79, 1923, p. 210.
- ⁸ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 79, 1923, p. 226.
- ⁹ H. B. Milner, *Quart. Journ. Geol. Soc.*, 78, 1922, p. 362, 364.
- ¹⁰ I. S. Double, *Proc. Geol. Assoc.*, 35, 1924, p. 340.
- ¹¹ A. Brammall, *Proc. Geol. Assoc.*, 39, 1928, p. 31.

General References.

- F. C. Phillips, "Crystals of Brookite tabular parallel to the basal plane." *Mineral. Mag.*, 23, 1932, p. 126.
 R. H. Rastall, *Geol. Mag.*, 75, 1938, p. 433.

NOTE ON THE INTERFERENCE FIGURE OF BROOKITE (DARTMOOR). (Quoted from A. Brammall, *Proc. Geol. Assoc.*, 39, 1928, p. 33.)

- "(a) Under the best conditions, the figure shows well-defined compound lemniscates approximating to arcs. In the 'straight' position it has the aspect of *fig. 1*, changing, on rotation through 45° , to *fig. 2* and *fig. 3* in succession.
 In *fig. 1* the N.-S. central bar is the more sharply defined and is flanked by reddish tints near the poles. The E-W bar is somewhat dispersed, the polar tints being dominantly greenish. The arc-like colour-bands are compounded of green and red, shading into yellow and orange in the inter-spaces. In each band, the red arc is more convex than the green, and the two overlap; the overlap segments are strikingly darker than the rest of the band.
- (b) Under less favourable conditions, the colour-bands shown in *figs. 1, 2* and *3* become indistinct or indiscernible: the colour-patterning shows an areal spread of tints (*fig. 1a*). On rotation through 45° four broad isogyral colour-bands evolve (*figs. 2a* and *3a*)—in place of the two sharply defined 'black' isogyres shown by a normal biaxial figure. In each of the phases *1a*, *2a* and *3a*, reddish tints dominate one pair of opposed quadrants; greenish tints dominate the other pair.
- (c) In the 'straight' position the figure shows the usual dark (neutral grey) cross. On the slightest rotation from this position each of the four arms of the cross becomes reddish on one side, greenish on the other (*figs. 4a* and *4b*). If rotation be continued through 45° , the green and red tints spread centrosymmetrically, in the manner shown in *figs. 2a* and *3a*."

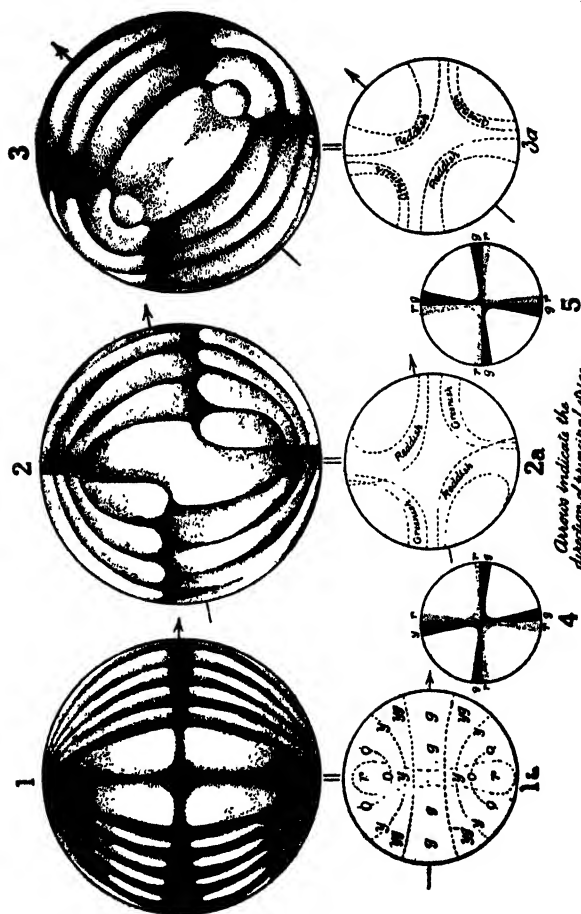
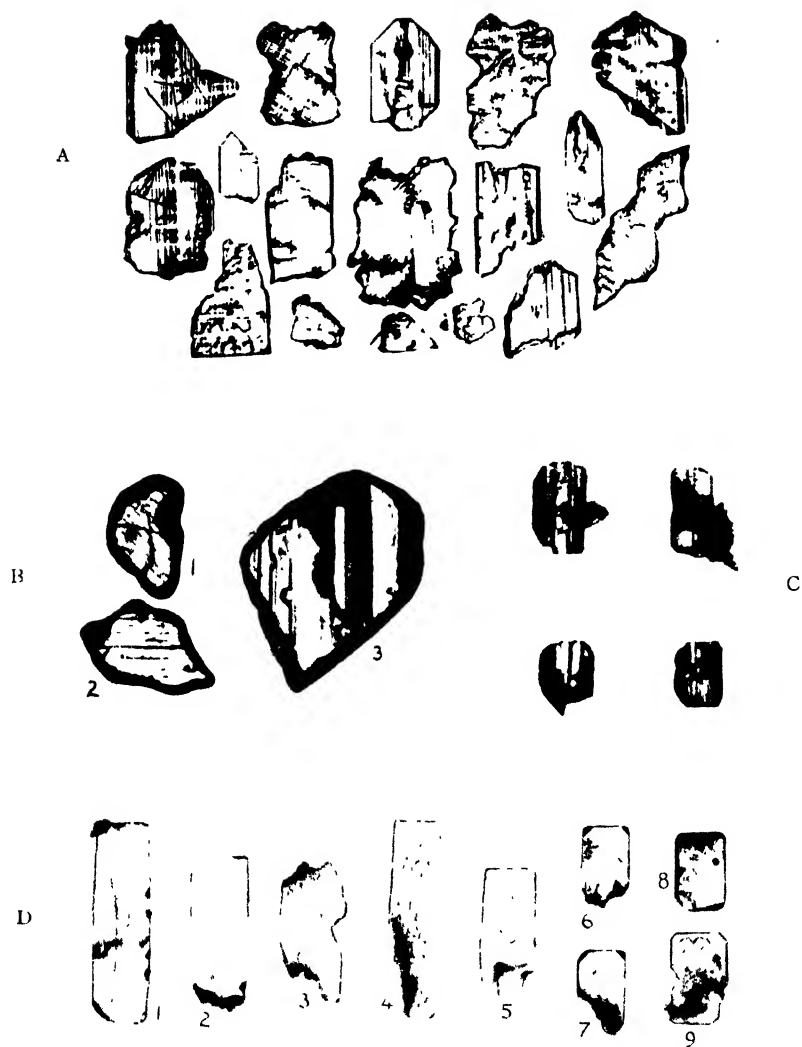
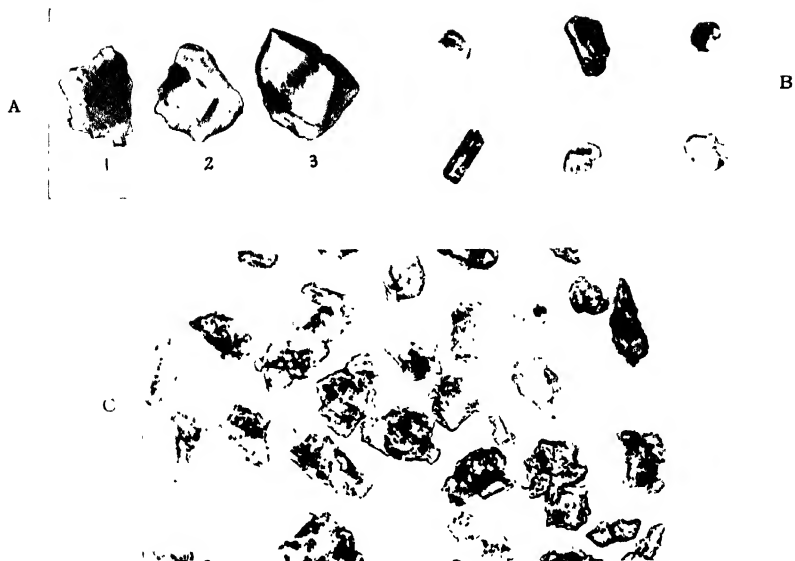


FIG. 78. Interference Figure of Brookite (Dartmoor).—A. Brannall.



A-D. BROOKITE

- A Typical Crystals and Fragments from Dartmoor. (From brush-drawings by A. Brammall.)
Grade-size 0.2-1.4 mm.
- B 1, 2. Worn detrital grains, Trias, Yorkshire [$\times 210$]
3. Worn detrital grain, Glacial Sand, Yorkshire [$\times 210$]
- C. Middle Jurassic, Yorkshire (Authigenic) [$\times 66$]
- D 1-7 Middle Jurassic, Yorkshire (Authigenic, tabular on ool.) [$\times 150$]
8, 9 Lower Carboniferous, Northumberland (Authigenic, tabular on ool.) [$\times 150$]
(Note. D 1-9 Optically anomalous grains from wash drawings by F. Smithson.)



A-C CALCITE

- A 1, 2. Upper Greensand, Chaldon Herring, Dorset (X 80)
 3. Shore Sand, Kynance, Cornwall (X 40)
 B Shore Sand, Dorset (X 23)
 C Fuller's Earth (Aptian), Surtey (Autochthon) (X 60)



D, E, F. CASSITERITE.

- D Typical Crystals and Fragments from Dartmoor. (From brush drawings by A. Brannall)
 Grade-size up to 8 mm
 E Alluvials, Nigeria Transmitted light (X 30)
 F The same Reflected light.
 / o face page 257.

BYTOWNITE

(PLAGIOCLASE FELSPAR GROUP)

Chem. Comp. AbAn_4 .*System.* Triclinic.*Habit.* Seldom well defined as crystals. Usually massive, prominent twinning on (010) with broad lamellæ.*Structure.* Massive, compact, microcrystalline.*Cleavage.* Perfect \parallel (100), distinct \parallel (010).*Fracture.* Irregular.*Hardness.* 6.*Spec. Grav.* 2.73.*Lustre.* Vitreous, pearly.*Colour.* Colourless, grey, green, white.*Mag. Prop.* Non-magnetic.*Elect. Prop.* Non-conductor.*Opt. Prop.* R.I. low, $\alpha = 1.566$, $\beta = 1.572$, $\gamma = 1.576$. Birefringence moderate, $\gamma - \alpha = 0.010$. Optically biaxial, negative. $Bxa = X$ inclined about 30° to (001) and 35° to (010). A. N. Winchell gives extinction angles $\perp X - 58^\circ$, $\perp Z - 49^\circ$, $\parallel (001) - 18^\circ$, $\parallel (010) - 31^\circ$, max. $\perp (010) + 42^\circ$. $2V = 82^\circ$. Dispersion $\rho > v$.*Characters in Sediments.* Bytownite is probably the rarest of the plagioclase feldspar group in basic igneous rocks and consequently its occurrence in detrital form is correspondingly restricted. Where suspected, its diagnosis depends on presence of twin lamellæ, identification of crystal face(s) presented by the grain or flake(s) and measurement of R.I. and extinction angles.*Occurrence.* In the soils of Kediri, Java.¹*Possible Sources of Derivation.* Basic igneous plutonic and volcanic rocks. More rarely anorthosite (gabbro practically free from pyroxene, composed chiefly of bytownite).*Reference.*¹ G. A. Neeb, *Overdruk uit de Handelingen v/h. 7de Ned. Ind Natuurwetenschappelijk Congres*, 1936, p. 695.**CALCITE**

[Pl. 14 A, B, C, facing p. 257.]

Chem. Comp. CaCO_3 .*System.* Trigonal.*Habit.* Highly varied and frequently complex. Commonly prismatic, rhombohedral, scalenohedral or twinned on (0001) or (0012).*Structure.* Crystalline or massive.*Cleavage.* Perfect \parallel unit rhombohedron (1011). Good parting \parallel (0112) in twin crystals, more rarely \parallel (1120).*Fracture.* Irregular, but rare.*Hardness.* Varies with composition, but usually about 3.*Spec. Grav.* 2.71-2.72.*Lustre.* Vitreous, pearly.*Colour.* Colourless, white or pale shades of yellow, red or brown, due to impurity. Transparent to translucent.*Mag. Prop.* Non-magnetic.*Elect. Prop.* Non-conductor.*Opt. Prop.* R.I. low for ω , high for ϵ . $\omega = 1.658$, $\epsilon = 1.486$. Birefringence very strong, $\omega - \epsilon = 0.172$. Optically uniaxial, negative. (1011)

cleavage plates show partial interference figure; symmetrical extinction.

Characters in Sediments. Usually occurs as highly irregular grains, slightly rounded. Twin striæ || the major diagonals of the cleavage flakes (1011) often observed. Diagnosed chiefly by lamellar twinning, "twinkling" effect noted on rotation of polariser, strong birefringence, uniaxial negative figure of distinctive type.

Occurrence. In the Old Red Sandstone of the West Midlands;¹ in the Permo-Triassic rocks of the Midlands;² in the Lower Greensand of Kent and Surrey;³ in the Upper Greensand of Dorset;⁴ in Oligocene "glass" sand, Fontainebleau, Paris;⁵ in the dune sands of South Wales;⁶ in surface deposits of S.E. Devonshire;⁷ in shore sand, Kynance, Cornwall.⁸

Possible Sources of Derivation. Chiefly from sedimentary rock masses, either as a primary or secondary constituent. Also from decomposition of lime-silicate minerals in igneous rocks. Recrystallised from shell-fragments.⁹

REMARKS.—Calcite very rarely occurs as simple rhombohedra in sediments; such forms are generally ascribable to dolomite. Like dolomite and magnesite, it differs from the other species of the calcite group (*e.g.* siderite, smithsonite) in having one R.I. lower than that of Canada balsam. Where diagnosis is doubtful, chemical tests must be made, especially for distinction from dolomite. The principal tests are:—(1) Vigorous effervescence with cold HCl; dolomite effervesces slowly, if at all. Both minerals react readily to warm HCl. (2) With ferric chloride gives reddish-brown deposit of ferric hydroxide; dolomite only affected after prolonged treatment. (3) *Lemberg's Test*: 60 parts H₂O, 4 parts Al₂Cl₆ and 6 of logwood chips (*hæmatoxylon campechianum*) boiled together for 25 minutes; when cool treat mineral with this solution: calcite takes the stain after 5 to 10 minutes, dolomite remains unaltered. For other tests, see A. Holmes, *Petrographic Methods*. (Murby, London), 1921, ch. vii.

References.

- ¹ W. F. Fleet, *Geol. Mag.*, 63, 1926, p. 512.
- ² W. F. Fleet, *Proc. Geol. Assoc.*, 38, 1927, p. 6.
- ³ G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915-16, p. 90.
- ⁴, ⁵ Author's observations.
- ⁶ A. Stuart, *Proc. Geol. Assoc.*, 35, 1924, p. 322.
- ⁷ W. G. Shannon, *Geol. Mag.*, 64, 1927, p. 145.
- ⁸ Author's observations.
- ⁹ P. G. H. Boswell, *Geol. Mag.*, 1915, p. 255.

CASSITERITE

[Pl. 14 D, E, F, facing p. 257.]

Chem. Comp. SnO₂.

System. Tetragonal.

Habit. Commonly euhedral. Short bipyramidal, prismatic or twinned on (101).

Structure. Crystalline, massive, granular.

Cleavage. Imperfect || (100), poor || (111), trace || (110).

Fracture. Subconchoidal, uneven.

Hardness. 6-7.

Spec. Grav. 6.8-7.1.

Lustre. Adamantine, submetallic or dull.

Colour. Brown, black, reddish-brown, more rarely pale yellow or greyish-white. Translucent to opaque.

Mag. Prop. Usually non-magnetic, but magnetic varieties known.

Elect. Prop. Moderate conductor.

Opt. Prop. R.I. very high, $\omega = 1.997$, $\epsilon = 2.093$. Birefringence strong. $\epsilon - \omega = 0.096$. Optically uniaxial, positive. Length slow. Straight extinction. Interference figure often "splits" into pseudo-biaxial type in certain varieties: small axial angle. Interference colours frequently masked by natural colour. Rarely pleochroic: ω = brown, yellow, red, pink; ϵ = grey-green, yellow, red.

Characters in Sediments. Commonly occurs as prismatic and pyramidal grains, or as irregular rolled crystals, either opaque with marked adamantine lustre or of composite colour in which brown and red of different shades predominate. The colour is often distributed irregularly in the grain, giving a blotchy appearance; or some individuals may present small translucent patches in an otherwise opaque mass. Detrital, like alluvial, cassiterite is extremely variable in character, especially as regards its pleochroism, which in examples from some localities is consistently developed. Inclusions in translucent varieties are common and are nearly always iron oxide. Zoning is frequent and some very beautiful examples of colour-band patterning are met with. Knee-shaped twins, characteristic of many alluvial occurrences, are rare as detrital grains. Well marked fluting or finer striae || principal axis are commonly noted in prismatic grains, while striae || pyramidal faces occur (Dartmoor).

Occurrence. In the New Red Sandstone of the West of England;¹ in the Bunter Pebble Bed of the West of England;² in the Greensand, Eocene, Oligocene and Pliocene deposits of the West of England;³ in the Pliocene deposits of Cornwall;⁴ in the dune sands of South Wales;⁵ in Dartmoor detritals;⁶ in Clay-with-Flints, Walton Heath, Surrey;⁷ in the shore sand of St. Ives Bay, Cornwall.⁸

Possible Sources of Derivation. From veins, pegmatites etc., associated with granitic rocks; from metalliferous lodes. Rarely a minor accessory species in granite itself.

REMARKS.—Cassiterite as a constituent of detrital sediments is probably more common than existing records suggest, but is liable to be confused with rutile, hypersthene, titanite or other "dusky" brown minerals. Microscopical diagnosis is by no means always unequivocal and the simple zinc and HCl test should always be resorted to wherever possible. This consists of the use of a metallic zinc bath in which the supposed cassiterite grains are placed, then covered with dilute HCl; the nascent hydrogen evolved results in an aluminium-grey coating to the tinstone, which can easily be detected under the microscope and is positive.

References.

- ¹ H. H. Thomas, *Quart. Journ. Geol. Soc.*, 65, 1909, p. 231.
- ² H. H. Thomas, *Quart. Journ. Geol. Soc.*, 58, 1902, p. 623.
- ³ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 79, 1923, p. 226.
- ⁴ H. B. Milner, *Quart. Journ. Geol. Soc.*, 78, 1922, p. 359, 364.
- ⁵ A. Stuart, *Proc. Geol. Assoc.*, 35, 1924, p. 321.
- ⁶ A. Brammall, *Proc. Geol. Assoc.*, 39, 1928, p. 36 and Pl. 2.
- ⁷ G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915-16, p. 89.
- ⁸ T. Crook and G. M. Davies, *Geol. Mag.*, 1909, p. 120.

General References.

- P. G. H. Boswell, "The Rarer Detrital Minerals of British Sedimentary Rocks." *Trans. Geol. Soc. Glasgow*, 18, 1926-27, p. 135.
 C. Raeburn and H. B. Milner, "Alluvial Prospecting." (Murby, London), 1927, p. 362 (for full description of alluvial occurrences).

CELESTITE

Chem. Comp. $\text{SrO} \cdot \text{SO}_3$.

System. Orthorhombic.

Habit. Tabular $\parallel (001)$; prismatic; less commonly pyramidal.

Structure. Crystalline, fibrous, radiating.

Cleavage. Perfect $\parallel (001)$, good $\parallel (110)$, imperfect $\parallel (010)$. Prismatic cleavage 75° .

Fracture. Irregular, distinct

Hardness. 3-3.5.

Spec. Grav. 3.95-3.97.

Lustre. Vitreous.

Colour. Colourless, white, pale blue, rarely pink.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. high, $\alpha = 1.622$, $\beta = 1.624$, $\gamma = 1.631$. Birefringence weak, $\gamma - \alpha = 0.009$. Optically biaxial, positive. $Bxa = Z \perp (100)$. Optic axial plane $\parallel (010)$. $X \parallel c$, $Z \parallel a$. Straight extinction \parallel prism-edge. $2V = 51^\circ$. $2E = 80^\circ$. Dispersion, $\rho < \nu$. Normally non-pleochroic. Blue varieties faintly pleochroic, maximum absorption $\parallel X$.

Characters in Sediments. Celestite, like barite and anhydrite, is almost invariably authigenic, associated with limestone, certain sandstones in which it occurs as a cementing medium, marls, gypsum and rock-salt. Consequently when isolated as detached flakes it tends to be of fantastic shape, i.e. the shape of the original interstice which it filled. There is little available on microscopical evidence alone to determine definitely this species, which is liable to confusion with related sulphates and with other colourless minerals. Since when it does occur it is usually prolific, little difficulty is experienced in applying the customary flame-test (crimson) or spectroscopic methods of discrimination. Insoluble in HCl.

Occurrence. In the New Red Sandstone of the West of England;¹ in the Triassic gypseous deposits and dolomites near Jena, Germany;² in Triassic sandstones and marls of Yate, Gloucestershire.³

Possible Sources of Derivation. From cementing (authigenic) media in calcareous and arenaceous rocks; from geodes and secondary masses in marls; from veins and metalliferous bodies.

References.

¹ H. H. Thomas, *Quart. Journ. Geol. Soc.*, 65, 1909, p. 234.

² E. Kalkowsky, *Zeitschr. deutsch. geol. Gesellschaft.*, 73, 1922, p. 1.

³ Well-known locality.

CEYLONITE (Pleonaste)

(SPINEL GROUP) [Pl. 15 A, facing p. 261.]

Chem. Comp. $(\text{Mg}, \text{Fe})\text{O} \cdot \text{Al}_2\text{O}_3$.

System. Isometric.

Habit. Octahedral, sometimes with dodecahedral development. Occasional twinning on (111) .

Structure. Crystalline.

Cleavage. Imperfect $\parallel (111)$.

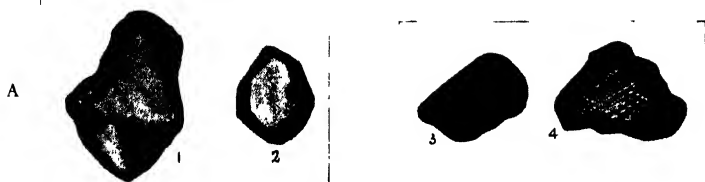
Fracture. Conchoidal.

Hardness. 8.

Spec. Grav. 3.84.

Lustre. Vitreous; splendent to dull.

Colour. Green, blue-green.

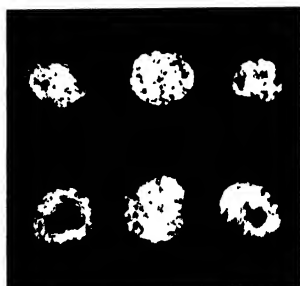


A. CEMONITE.

- 1, 2 Alluvials, Gold Coast, West Africa [x 15]
 3. Pliocene, S. of Elham, Folkestone [x 40]
 4 From Monazite Sand, Travancore, India [x 25]



B



C

B, C. CHALCEDONY

- B. Detrital Flint, Shore Sand, Sussex [x 50]
 C. Cotallian, Yorkshire (Authigenic) [x Nicols] [x 200]



D



E



F

D, E, F. CHIASTOLITE.

- D, 1 Pleistocene Gravel, Bayford, Herts. [x 10]
 D 2, 3 Shooters Hill Gravel, London. [x 40]
 E River Sand, R. Caldew, Cumberland, [x 22.]
 F. Shore Sand, Cumberland [x 23.]

To face page 261.

PLATE 15.

Mag. Prop. Weakly magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. very high, 1.75-1.79 (A. N. Winchell), varying with composition and depth of colour. Isotropic.

Characters in Sediments. Usually exhibits some degree of rounding, but the simple octahedral habit is very characteristic and is, in fact, one of the chief diagnostic properties of this mineral in detrital sediments. It is sometimes highly fractured when it may resemble green garnet, a mineral of similar refractive index; green garnet (*vars.* Uvarovite, p. 350, Andradite, p. 238), often exhibits anomalous polarisation colours, very rare with ceylonite. This mineral seldom has inclusions; green garnet is liable to show them.

Occurrence. Possibly in the Lower Keuper Sandstone of the English Midlands;¹ in the Northampton Ironstone;² rarely in the Sands of the Upper Lias—Inferior Oolite of the West of England;³ in the Spilsby Sandstone (Lower Cretaceous);⁴ in the Thanet Beds of the London Basin;⁵ in the Bagshot Beds of Essex;⁶ in the Norwich Crag (newer Pliocene) of the East of England;⁷ in the Lenham (Pliocene) Beds of Sanderstead, Surrey;⁸ occasionally in the shore sands of East England and Brittany;⁹ in Dartmoor detritals.¹⁰

Possible Sources of Derivation. Basic and ultrabasic igneous rocks; metamorphosed limestone, dolomite and argillaceous rocks; aureole and xenolithic hornfels containing corundum, cordierite etc.

REMARKS.—An infrequent species, though it seems to be a constant constituent of the Lenham Beds; probably often confused with garnet and possibly members of the chlorite group; see also under Spinel (p. 339) for possible method of distinction from garnet.

References.

- ¹ W. F. Fleet, *Geol. Mag.*, 62, 1925, p. 124.
- ² J. G. A. Skerl, *Proc. Geol. Assoc.*, 38, 1927, p. 375.
- ³ P. G. H. Boswell, *Geol. Mag.*, 61, 1924, p. 257.
- ⁴ F. T. Ingham, *Proc. Geol. Assoc.*, 40, 1929, p. 1.
- ⁵ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 71, 1915, table IV.
- ⁶ S. W. Wooldridge, *Proc. Geol. Assoc.*, 35, 1924, p. 377.
- ⁷ I. S. Double, *Proc. Geol. Assoc.*, 35, 1924, p. 338.
- ⁸ F. Gossling and S. W. Wooldridge, *Proc. Geol. Assoc.*, 37, 1926, p. 99.
- ⁹ Observations of F. T. Ingham and the author.
- ¹⁰ A. Brammall, *Proc. Geol. Assoc.*, 39, 1928, p. 47.

General Reference.

P. G. H. Boswell, "The Rarer Detrital Minerals of British Sedimentary Rocks." *Trans. Geol. Soc. Glasgow*, 18, 1926-27, p. 135.

CHALCEDONY

[Pl. 15 B, C, facing p. 261.]

Chem. Comp. SiO₂.

System. Doubtful.

Habit. Botryoidal, massive.

Structure. Microcrystalline, fibrous.

Cleavage. None.

Fracture. Conchoidal, splintery.

Hardness. 6.

Spec. Grav. 2.55-2.63.

Lustre. Waxy, resinous.

Colour. White, pale blue, yellow, brown. (See varieties below.)

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low, $n=1.537$. Birefringence weak, $\omega-\epsilon=0.007$ (A. N. Winchell). Optical characters not known definitely. Fibres

believed to be biaxial, positive and give straight extinction. Elongated along *bzo*, i.e. negative (*H. A. Miers*). In some cases fibres have positive elongation || γ (*A. N. Winchell*). Other varieties exhibit aggregate polarisation.

Characters in Sediments. Grains usually angular, white or pale blue, sometimes with distinct layering or banding, seen to advantage with vertical illumination. Diagnosed by its lower S.G. than quartz, lower R.I. than Canada balsam, its fibrous character seen under high power magnification and anomalous optical properties.

Occurrence. For *Chalcedony*: in the Wenlock Limestone, England;¹ in the Silurian Sediments near Melbourne, Australia;² in the Franciscan limestone (Trias) of California;³ in the Upper Lias-Inferior Oolite of the West of England;⁴ in the Bargate Stone (Lower Greensand) near Guildford, Surrey;⁵ in certain horizons of British Chalk;⁶ in the Eocene Lake Bed deposits of Utah and Colorado, U.S.A.;⁷ in the river and dune sands of Italian Somaliland;⁸ in deposits at the bottom of Lake Como, Italy;⁹ in the Mallee soil of Western Australia.¹⁰ For *Chert* and *Flint*: in the Upper Lias-Inferior Oolite Sands of the West of England;¹¹ in the Cretaceous and Tertiary rocks of the West of England;¹² in the Cretaceous rocks of the Croydon Regional Survey Area, Surrey;¹³ in the Dune Sands of South Wales.¹⁴

Possible Sources of Derivation. Geodes, cavities, veins in decomposed igneous rocks. Inorganic: siliceous deposits from aqueous solution.

REMARKS.—*Chalcedony* is a highly variable mineral to which, when coloured, various names have been given, as also to mixtures with *Opal* (p. 320) and *Quartz* (p. 331). *Agate* is banded and variegated chalcedony. *Bloodstone* is *Plasma* (q.v. below) spotted with *Jasper*. *Cornelian* is the red variety. *Chrysoprase* is green chalcedony, colour due to nickel. *Heliotrope* is the same as *Bloodstone*. *Jasper* is a mixture of quartz with clay, limonite, iron oxide etc. *Moss Agate* is a variety of *Agate*. *Onyx* is a variety of *Agate*. *Plasma* is pale green chalcedony. *Prase* is green quartz in which chlorite is the pigment. *Sard* is brown-red, horn-like chalcedony.

Closely allied are *Chert*, *Flint* and *Hornstone*, a flinty variety of chalcedony often associated with volcanic rocks. *Chert* grains frequently occur as conspicuous constituents of detrital sediments; such grains may preserve traces of organic structure or they may be associated with pellets of pyrite. They frequently exhibit aggregate polarisation and are far more varied in character than pure chalcedony. Average particles are usually optically inert and are diagnosed chiefly by their appearance by reflected light, also by fracture. For fuller description of both chert and flint, see Chapter X, p. 401.

References.

- ¹ E. Wethered, *Quart. Journ. Geol. Soc.*, 49, 1893, p. 236.
- ² W. G. Langford, *Proc. Roy. Soc. Victoria*, 29, 1916, p. 40.
- ³ E. F. Davis, *Univ. California Publ., Bull. Dept. Geol. Sci.*, 11, 1918, p. 1.
- ⁴ P. G. H. Boswell, *Geol. Mag.*, 61, 1924, p. 252.
- ⁵ W. F. Hume, in F. Chapman, *Quart. Journ. Geol. Soc.*, 50, 1894, p. 677.
- ⁶ I. S. Double, *Journ. Roy. Micros. Soc.*, 47, 1927, p. 226.
- ⁷ W. H. Bradley, *U.S. Geol. Surv., Prof. Paper* 158-A, 1929.
- ⁸ E. Artini, *Atti Soc. ital. Sci. nat.*, 54, 1915, p. 137.
- ⁹ E. Artini, *Rend. R. Ist. lombardo*, 36, 1903, p. 596.
- ¹⁰ D. A. Carroll, *Journ. Roy. Soc. West Australia*, 20, 1933-4, p. 100.
- ¹¹ P. G. H. Boswell, *Geol. Mag.*, 61, 1924, p. 252.
- ¹² P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 79, 1923, p. 226.
- ¹³ G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915-16, p. 87.
- ¹⁴ A. Stuart, *Proc. Geol. Assoc.*, 35, 1924, p. 325.

CHERT

See Chalcedony, p. 261.

CHIASTOLITE

(VARIETY OF ANDALUSITE, p. 236.)

[Pl. 15 D, E, F, facing p. 261.]

Chief mineralogical properties as for Andalusite.

Characters in Sediments. Where graphitic or carbonaceous inclusions are concentrated within the mineral grain so as to exhibit a tessellated or geometrical design, e.g. a black cross, the variety "chiastolite" is diagnosed. There is, however, some difference of opinion among petrographers as to what should and what should not be called "chiastolite," since every gradation is met with in detrital sediments from colourless andalusite with a few irregularly scattered carbonaceous inclusions to those grains in which the black cross is definite. I. S. Double states, "The quantity and the mode of arrangement of the black inclusions is very variable. When part or all of the black cross associated with the varietal characters of chiastolite has been seen, that mineral is recorded."⁴ Although this only applies to a specific instance (late Tertiary deposits of the East of England), it is, in the author's opinion, the correct interpretation in all circumstances and where the inclusions are disseminated quite arbitrarily in the grains, these are better recorded as andalusite.

On the whole definite grains of chiastolite seldom show pleochroism so characteristic of many occurrences of andalusite and grains preserving the complete black cross are uncommon. I. S. Double illustrates four types of chiastolite in his paper; P. G. H. Boswell also figures two examples from the Oligocene beds of Devonshire. Detrital chiastolite is more often than not irregular in form, though occasionally the orthorhombic prism is preserved, when the grain exhibits straight extinction.

Occurrence. In the Sands of the Upper Lias—Lower Inferior Oolite of the West of England(?);¹ in the Oligocene Beds of the Bovey Basin, Devonshire;² in the gravels of doubtful age at Riddaford Water, Bovey, Devonshire;³ in the Red Crag and Coralline Crag (Pliocene) of the East of England;⁴ in the Lenham Beds of Sanderstead, Surrey⁵ and of the Folkestone district;⁶ in the matrix of the Pebble Gravel of the Hertfordshire plateau;⁷ in the Chalky-Jurassic Boulder Clay of Foxhall Road, Ipswich;⁸ in the Basement Clay at Dimlington.⁹

Possible Sources of Derivation. Metamorphosed argillaceous rocks, e.g. chiastolite slate.

REMARKS.—F. Smithson states that in sands and soils derived from the Skiddaw slate most of the chiastolite grains tend to rest on a prism face and show only a dark "core." Only a small proportion can be made to stand on (oor) and show the cross pattern.¹⁰

References.

- ¹ P. G. H. Boswell, *Geol. Mag.*, 61, 1924, p. 258.
- ² P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 79, 1923, p. 218, 220.
- ³ *Ibid.*, p. 223
- ⁴ I. S. Double, *Proc. Geol. Assoc.*, 35, 1924, p. 337, 339.
- ⁵ F. Gossling and S. W. Wooldridge, *Proc. Geol. Assoc.*, 37, 1926, p. 98.
- ⁶ Author's observations.
- ⁷ S. W. Wooldridge and D. M. C. Gill, *Proc. Geol. Assoc.*, 36, 1925, p. 171.
- ⁸ P. G. H. Boswell and J. Reid Moir, *Journ. Roy. Anthropol. Inst.*, 63, 1923, p. 229.
- ⁹ H. C. Versey, *Trans. Leeds Geol. Assoc.*, 20, for 1923-29, 1930, p. 17, 20.
- ¹⁰ Written communication.

CHLORITE GROUP

This group includes essentially hydrous silicates of aluminium and magnesium with ferric and ferrous iron, sometimes chromium. The minerals frequently represent alteration products of amphiboles and micas. Some minerals, e.g. antigorite (p. 242) often assigned to what was defined as a "serpentine group" are now recognised as "end-members" of the chlorite group and this practice is followed herein. The following is a list of the more important species of the chlorite group: only those recorded from sediments are dealt with in this volume, page references being given accordingly:—

Amesite.
Antigorite (p. 242).
Clinochlore (p. 268).
Daphnite.
Delessite (p. 273).

Diabantite.
Jenkinsite.
Penninite (p. 323).
Repiddite.
Thuringite.

From the standpoint of sedimentary petrography it is rare to find references to specific members of the chlorite group in the literature. Usually the word "chlorite" is recorded for the somewhat nondescript, green or greenish yellow "ultra-blue" polarising grains which, for want of definite optical properties, seldom can be more precisely tied down. The so-called "chlorite" derived from relaxed basic igneous rocks (more particularly their ferro-magnesian constituents) is poorly individualised as crystal and certainly rare in sediments as either penninite, clinochlore or other species. Thus where any doubt exists, the mineral is better designated as "chloritic matter" rather than "chlorite" *per se*, implying considerable variation in composition according to precise nature of parent minerals and destabilising environment.

For comparison of his examples with detrital species having definite optical properties, the reader is referred to the four principal members of the group, *antigorite*, *clinochlore*, *delessite* and *penninite*, fully treated herein on the pages indicated above.

In so far as records of "chlorite" in sediments may be of value, the following British occurrences may be cited:—

Occurrence. In the Cambrian, Devonian, Carboniferous and Permian Triassic rocks of the English Midlands;¹ in the Old Red Sandstone of the West Midlands;² in the New Red Sandstone of the West of England;³ in the Upper Lias—Lower Inferior Oolite of the West of England;⁴ in the Northampton Ironstone;⁵ in the Pliocene sands of West Cornwall;⁶ in the later Tertiary deposits of the East of England;⁷ in the dune sands of South Wales.⁸

References.

- ¹ W. F. Fleet, *Geol. Mag.*, 62, 1925, p. 98.
- ² W. F. Fleet, *Geol. Mag.*, 63, 1926, p. 505.
- ³ H. H. Thomas, *Quart. Journ. Geol. Soc.*, 65, 1909, p. 239.
- ⁴ P. G. H. Boswell, *Geol. Mag.*, 61, 1924, p. 256.
- ⁵ J. G. A. Skerl, *Proc. Geol. Assoc.*, 38, 1927, p. 382.
- ⁶ H. B. Milner, *Quart. Journ. Geol. Soc.*, 78, 1922, p. 357. 362, 365
- ⁷ I. S. Double, *Proc. Geol. Assoc.*, 35, 1924, p. 342.
- ⁸ A. Stuart, *Proc. Geol. Assoc.*, 35, 1924, p. 324.

CHLORITOID

(CHLORITOID—OTTRELITE GROUP)

[Pl. 16 A, B, facing p. 268.]

Chem. Comp. (Fe,Mg)O.Al₂O₃.SiO₂.H₂O.*System.* Monoclinic (pseudo-hexagonal) or triclinic.*Habit.* Similar to mica: in (001) plates. Sometimes twinned.*Structure.* Crystalline; radiating aggregates; curved.*Cleavage.* Good || (001), imperfect prismatic || (110); imperfect || (443) inclined about 90° to (001) and about 60° to one another (*J. P. Idings*). Parting || (010).*Fracture.* Irregular, brittle.*Hardness.* 6.5.*Spec. Grav.* 3.26-3.57.*Lustre.* Pearly.*Colour.* Dark green to greenish black, indigo.*Mag. Prop.* Weakly magnetic.*Elect. Prop.* Non-conductor.*Opt. Prop.* R.I. high, $\alpha = 1.720$, $\beta = 1.722$, $\gamma = 1.731$. Birefringence moderate, $\gamma - \alpha = 0.011$. Optically biaxial, positive. Optic axial plane || (010). $Bxa = Z$ inclined at 3°-30° with \perp (001). $X = b$. $2V = 36^\circ - 60^\circ$. $2E = 64^\circ - 118^\circ$. Horizontal dispersion, $\rho > \nu$, strong. Pleochroism distinctive: X =shades of green, Y =indigo or blue, Z =yellow or yellowish-green.*Characters in Sediments.* Detrital chloritoid is not a common mineral, but it has been definitely determined in a few instances in British sediments (see below). P. G. H. Boswell has described the characters of chloritoid in some detail: "... as scaly flakes . . . or wisps . . . often consisting of several flakes partly superposed. A second cleavage at about 90 degrees to the almost perfect basal cleavage is sometimes seen running across the flakes, and a third cleavage occurs at about 70 degrees to the second cleavage. . . . Average refractive index for sodium light . . . is >1.710 and <1.715 , but is nearer the former value. . . . Pleochroism distinctive . . . absorption being moderately strong. The scheme is, parallel to X (that is, approximately, second cleavage) dirty green or olive-coloured, parallel to Y indigo to smoky-blue. The wisps show less well-marked changes of colour. The birefringence is usually very low, ultra-blues, ultra-browns and indigo tints . . . occasionally first order greys and yellows are seen. Most of the flakes give a biaxial figure, the emergence of the acute bisectrix being almost central. The sign is positive, and the isogyres frequently show well-marked dispersion. The wisps show straight extinction on the length." Chloritoid from the shore sands of Brittany, observed by the author, is identified chiefly by its blue or bluish-green colour, high refractive index, low birefringence, strong pleochroism and dispersion of the optic axes, interference figure and sign, in all of which properties it agrees closely with the foregoing data. It tends to be scaly, showing a delicate, laminated structure, the "wisp" varieties being less common. In very small grains its diagnosis is by no means always certain.*Occurrence.* In sands of the Upper Lias-Lower Inferior Oolite of the West of England;¹ in the Northampton Ironstone;² in the Cotteswold Sands and Inferior Oolite limestone at Shipton Moyne;³ in the Jurassic sandstones of Yorkshire;⁴ in the Upper Kimmeridge Clay and Portland Sand of Dorset, Wiltshire, Oxfordshire and Buckinghamshire;⁵ in the Hunstanton Red rock;⁶ in the lower part of the Great

Ouse Basin;⁷ from beds of sand and clay sampled from two borings in the plain of Lombardy, Northern Italy;⁸ in shore sands from various localities in Southern Brittany.⁹

Possible Sources of Derivation. Crystalline schists, phyllites and quartzites. From reconstituted argillaceous sediments.

REMARKS.—The closely allied manganese-bearing silicate, Ottrelite, is fully described on p. 323.

References.

- ¹ P. G. H. Boswell, *Geol. Mag.*, 61, 1924, p. 254.
- ² J. G. A. Skerl, *Proc. Geol. Assoc.*, 38, 1927, p. 382.
- ³ P. G. H. Boswell, *Proc. Cotteswold Nat. Field Club*, 27, 1923, p. 213.
- ⁴ R. H. Rastall, *Proc. Yorks. Geol. Soc.*, 22, 1932, p. 93.
- ⁵ E. Neaverson, *Proc. Geol. Assoc.*, 36, 1925, p. 250.
- ⁶ R. H. Rastall, *Geol. Mag.*, 67, 1930, p. 436.
- ⁷ R. H. Rastall, *Quart. Journ. Geol. Soc.*, 82, 1926, p. 116.
- ⁸ I. Chelussi, *Boll. Soc. geol. ital.*, 43, 1924, p. 161.
- ⁹ Observations of F. T. Ingham and the author.

General Reference.

- P. G. H. Boswell, "The Rarer Detrital Minerals of British Sedimentary Rocks." *Trans. Geol. Soc. Glasgow*, 18, 1926-27, p. 138.

CHROMITE

(SPINEL GROUP)

Chem. Comp. $\text{FeO} \cdot \text{Cr}_2\text{O}_3$.

System. Isometric.

Habit. Octahedral or combination of octahedron and dodecahedron.

Structure. Rarely crystalline, commonly massive, granular.

Cleavage. None.

Fracture. Uneven.

Hardness. 5.5.

Spec. Grav. 4.32-4.57.

Lustre. Metallic to submetallic, rarely dull.

Colour. Black or brownish-black, frequently with purple tarnish.

Mag. Prop. Moderately magnetic.

Elect. Prop. Good conductor.

Opt. Prop. Opaque in transmitted light, except in very thin section when the deep brown colour and isotropic character are apparent. R.I. very high, $n = 2.070$.

Characters in Sediments. Occurs as rounded octahedral grains or as sub-angular and irregular fragments. Deposits derived from ultrabasic rocks often contain a high percentage of this mineral, which is identified chiefly by its grey submetallic lustre in vertical reflected light and by its colour and form. Locally in alluvial sands suitably derived.

Occurrence. In the Middle Chalk of Beer Head, S.E. Devonshire;¹ ? in the dune sands of South Wales;² in shore sands of Kynance Cove, Coverack etc., Lizard district, Cornwall;³ in the Titaniferous Iron-Sand of Porth Dinlleyn, Carnarvonshire;⁴ in the gabbro soil of Borneo;⁵ in the sands of the Kettleman Hills, California, U.S.A.⁶

Possible Sources of Derivation. Chiefly from peridotites, serpentines and associated ultrabasic rocks; more rarely from crystalline schists.

REMARKS.—The microscopical determination of chremite is not always convincing and, if possible, should be supplemented by chemical test. (With borax bead, chromium yields green colour in both oxidising and reducing flames.)

References.

- ¹ G. M. Davies, *Geol. Mag.*, 1919, p. 506.
- ² A. Stuart, *Proc. Geol. Assoc.*, 35, 1924, p. 321.
- ³ Author's observations.
- ⁴ T. H. Cope, *Proc. Liverpool Geol. Soc.*, 9, 1902, p. 208.
- ⁵ D. A. Carroll, *Journ. Roy. Soc. West Australia*, 20, 1933-4, p. 100.
- ⁶ M. N. Bramlette, *Bull. Amer. Assoc. Petrol. Geol.* 18, 1934, p. 1559.

General References.

- P. G. H. Boswell, *Proc. Liverpool Geol. Soc.*, 13, 1923, p. 273. (Record of chromite from sediments obtained on the "Challenger" Expedition.)
 C. Raeburn and H. B. Milner, "Alluvial Prospecting." (Murby, London), 1927, p. 367 and references cited (for alluvial chromite).

CHRYBOTILE [Pl. 16 c, facing p. 268.]

Chem. Comp. $3\text{MgO} \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$.

System. Orthorhombic (?).

Habit. Fibres, elongated || c.

Structure. Crystalline, fibrous.

Cleavage. Poor || (110) at 130° .

Fracture. Irregular.

Hardness. 4.

Spec. Grav. 2.5.

Lustre. Pearly, resinous.

Colour. Green, yellow, grey. Translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low, $\alpha = 1.508$, $\beta = 1.512$, $\gamma = 1.522$. Birefringence moderate, $\gamma - \alpha = 0.014$. Optically biaxial, positive. Optic axial plane || (010). $Bxa = Z$ || c, i.e. positive elongation. $X = b$. $2V = 30^\circ - 35^\circ$. Pleochroism faint, $Z = \text{green-yellow} > Y = \text{green to colourless} > X = \text{green to colourless}$.

Characters in Sediments. Chrysotile in sediments is characterised by its fibrous habit, yellow-green colour, low R.I., positive elongation and straight extinction, except in cases where anomalous "ultra blue" interference colours may prevail. It differs from antigorite (p. 242) by its fibrous, rather than lamellar structure and sign.

Occurrence. Recorded as "Serpentine": In the Devonian and Culm sediments of the Torquay district;¹ in the Permian rocks of the Torquay Promontory;² in the New Red Sandstones of the West of England;³ in the sands of the Upper Lias-Lower Inferior Oolite of the West of England;⁴ in the shore sands in proximity to the serpentine masses of the Lizard district, Cornwall;⁵ in recent deposits of Pavia etc., Northern Italy;⁶ in deposits of doubtful age (?Eocene) of Marazion, Cornwall.⁷

Possible Sources of Derivation. Serpentine rocks. Decomposition product of ferro-magnesian minerals,

REMARKS.—Most of the so-called "serpentine" recorded from British sediments is probably chrysotile, far less commonly antigorite (p. 242) or it may be another member of the chlorite group (p. 264). See general note under Serpentine (p. 335).

References.

- ¹ W. G. Shannon, *Proc. Geol. Assoc.*, 39, 1928, p. 139, 142.
- ² W. G. Shannon, *Proc. Geol. Assoc.*, 38, 1927, p. 134.
- ³ H. H. Thomas, *Quart. Journ. Geol. Soc.*, 65, 1909, p. 239.
- ⁴ P. G. H. Boswell, *Geol. Mag.*, 61, 1924, p. 252.
- ⁵ Author's observations.
- ⁶ E. Tacconi, *Rend. R. Ist. lombardo*, ser. 2, 34, 1901, p. 873.
- ⁷ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 79, 1923, p. 213, 226.

CLINOCHLORE

(CHLORITE GROUP)

Note: See also Chlorite, p. 264.

Chem. Comp. $5\text{MgO} \cdot (\text{Al}, \text{Cr})_2\text{O}_3 \cdot 3\text{SiO}_2 \cdot 4\text{H}_2\text{O}$.

System. Monoclinic.

Habit. Pseudo-hexagonal plates with bevelled edges; tabular, prominent basal plane. Polysynthetic twinning common.

Structure. Foliated, massive, rarely crystalline.

Cleavage. Perfect \parallel (001).

Fracture. Irregular.

Hardness. 2-3.

Spec. Grav. 2.76-2.78.

Lustre. Vitreous, pearly (001).

Colour. Green, olive, less commonly yellow, white.

Mag. Prop. Weakly to non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low, $\alpha = 1.579$, $\beta = 1.579$, $\gamma = 1.584$. Birefringence weak, $\gamma - \alpha = 0.005$. Optically biaxial, positive. (Negative form also known, with R.I. $\beta = 1.594$, birefringence 0.010.) Optic axial plane (010). $Bxa = Z \perp (001)$. Rarely $Z \wedge \perp (001) = 2^\circ 30'$ (A. N. Winchell). $2V = 0^\circ \pm$. Weak inclined dispersion $\rho < \nu$. Pleochroism $X = \text{pale green}$, $Y = \text{pale green}$, $Z = \text{pale yellow green}$.

Characters in Sediments. It is rare that clinochlore is specifically determinable in detrital sediments. The green grains of low R.I., weak birefringence (often "ultra-blue") commonly met with are not clinochlore *per se* but of variable and complex composition, best designated "chloritic matter." Clinochlore is characterised by its green colour, weak but distinctive pleochroism, normally positive sign, low R.I. and birefringence. It is rarer than penninite (p. 323) and differs from that species particularly in the very low birefringence ("ultra-blue" abnormal interference colours) exhibited by the latter, not typical of clinochlore.

Occurrence. See p. 264 for records of detrital "chlorite."

Possible Sources of Derivation. Slates, phyllites and metamorphic rocks.

General Reference.

- J. Oreel, "Recherches sur la composition chimique des chlorites." *Soc. franç. mineralogie Bull.*, 50, 1927, p. 75.



A, B CHLORITOID.
 A 1 Shore Sand, Dinard, Brittany [x 4]
 A 2 Recent Sand Le Pouldu, Brittany [x 45]
 B Locene, Virginia U.S.A. [x 60]



C. CHRYSOTILE.
 1 3 Shore Sand, Kynance, Cornwall [x 45]



D. CORDIERITE.
 Swellon, Dartmoor [x 24]

CLINOZOISITE

(EPIDOTE GROUP)

Chem. Comp. $4\text{CaO} \cdot 3\text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2 \cdot \text{H}_2\text{O}$.**System.** Monoclinic.**Habit.** Tabular || (100), elongated || b; striations || b.**Structure.** Crystalline.**Cleavage.** Perfect || (001). Imperfect || (100).**Fracture.** Irregular.**Hardness.** 6.5.**Spec. Grav.** 3.35-3.38.**Lustre.** Vitreous.**Colour.** Colourless, yellow, pale green, brown.**Mag. Prop.** Non-magnetic.**Elect. Prop.** Non-conductor.

Opt. Prop. R.I. high, $\alpha = 1.715$, $\beta = 1.720$, $\gamma = 1.725$. Birefringence moderate, $\gamma - \alpha = 0.010$. Optically biaxial, positive. (Negative forms are known.) Optic axial plane || (010). $Bxo = X$ inclined to c at $2^\circ - 12^\circ$. $Bxa = Z$ inclined to (001) cleavage = $24^\circ - 14^\circ$ (A. N. Winchell). $Y = b$. $2V = 66^\circ$. $2E = 138^\circ$. Dispersion strong, $\rho < \nu$. Pleochroism $X = \text{green}$, $Y = \text{pink or green}$, $Z = \text{deep red or green}$. "Ultra-blue" anomalous birefringence colours occasionally exhibited.

Characters in Sediments. Clinozoisite, though rarely recorded from sediments, is probably commoner than generally anticipated. It is of more frequent occurrence in other conditions than zoisite. Detrital grains are colourless or pale yellow, generally determined by (001) cleavage, having high R.I., moderate birefringence (occasional "ultra-blue" interference tints) and weak pleochroism. Differs from zoisite in its oblique extinction (in (010) grains measured on cleavage traces) and larger optic axial angle. Inclusions may be amphibole microlites.

Occurrence. Dune sands, S. Wales;¹ river and dune sands of Chinese Turkestan.²

Possible Sources of Derivation. Crystalline schists, metamorphosed basic igneous rocks; also from saussurite, an alteration product of lime-soda feldspar.

References.

¹ A. Stuart, *Proc. Geol. Assoc.*, 35, 1924, p. 321.

² A. Vendl, *Mitt. Jahrb. k.-ung.-Geol. Austria*, 21, 1913, p. 1.

COLLOPHANE**Chem. Comp.** $\text{CaO} \cdot \text{P}_2\text{O}_5 \cdot \text{H}_2\text{O} \cdot \text{CO}_2$ etc.**System.** Non-crystalline: amorphous.**Habit.** Massive.**Structure.** "Stratified"—as deposited.**Cleavage.** None.**Fracture.** Conchoidal.**Hardness.** 3.5.**Spec. Grav.** 2.6-2.9.**Lustre.** Dull.**Colour.** White.**Mag. Prop.** Non-magnetic.**Elect. Prop.** Non-conductor.

Opt. Prop. R.I. variable, $n=1.569-1.63$. Optically isotropic, some examples weakly birefringent due to strain.

Characters in Sediments. Irregular, shapeless grains of white or grey colour, to be anticipated in certain "phosphate" environments. Also in the form of rounded grains or "pellets" not unlike large oolites.

Occurrence. Miocene limestone, Florida, U.S.A.; Pliocene and Quaternary deposits, Florida; shore deposits, Gulf Coast, Florida; Jacksonville, Florida; at Savannah and Brunswick, Georgia, U.S.A.; at Charleston, South Carolina, U.S.A.;¹ at Tybee and St. Simon Island, Georgia;² in beach sands between St. John's River and St. Augustine, Florida, U.S.A.³

Possible Sources of Derivation. Phosphatic nodules, bones, phosphates in general.

REMARKS.—See also Chapter X, p 419, and Chapter XIII, p. 504.

References.

¹ Communication from J. H. C. Martens, Florida State Geological Survey, to the author.

² J. H. C. Martens, *Bull. Geol. Soc. Amer.*, 46, 1935, p. 1563.

³ J. H. C. Martens, 19th Ann. Rep. Florida State Geol. Surv., 1928, p. 130.

CORDIERITE [Pl. 16 D, facing p. 268.]

Chem. Comp. $4(\text{MgFe})\text{O} \cdot 4(\text{Al}_2\text{O}_3) \cdot 10\text{SiO}_2 \cdot \text{H}_2\text{O}$.

System. Orthorhombic.

Habit. Euhedral short prismatic crystals; often twinned pseudo-hexagonal "aragonite" type on (110) or (130).

Structure. Crystalline, granular.

Cleavage. Good || (010), poor || (100) and (001).

Fracture. Subconchoidal.

Hardness. 7-7.5.

Spec. Grav. 2.57-2.66.

Lustre. Vitreous.

Colour. Shades of blue, yellow, brown.

Mag. Prop. Moderately magnetic.

Elect. Prop. Poor conductor.

Opt. Prop. R.I. low, $\alpha=1.534$, $\beta=1.538$, $\gamma=1.540$. Birefringence weak, $\gamma-\alpha=0.006$. Optically biaxial, negative. Optic axial plane || (100). Straight extinction || prism edge. $Bxa=X || c \perp (001)$. $Y || a$, $Z || b$. Optic axial angle variable, $2V=40^\circ$ to 84° . $2E=151^\circ$. Usually pleochroic: $Y=\text{dark blue}$ $>Z=\text{light blue}$ $>X=\text{yellowish white}$. Weak dispersion, $\rho < \nu$.

Characters in Sediments. Generally occurs as small subangular grains, almost colourless, weakly pleochroic and birefringent. Minute and opaque inclusions are common; these may be surrounded by pleochroic halos, e.g. zircon, apatite and dumortierite. A. Brammall also records zircon, monazite, quartz, feldspars, biotite, white mica, rutile needles, granules of green spinel and black opaque matter. In its unaltered form it is of rare occurrence in sediments, pinite being the usual product met with. Pinite is recognised by its green or greenish-brown colour, micaceous habit and its tendency to form cryptocrystalline aggregates. On the subject of alteration products of cordierite and its instability in detrital sediments, see A. Brammall.⁵

Occurrence. In the Millstone Grit of Yorkshire;¹ in the micaceous sandstones of the Pennant Series;² ? in the New Red Sandstone of the West of England;³ in the Franciscan Sandstone (Trias), California;⁴ in Dartmoor detritals;⁵ in sands of the River Danube, near Budapest;⁶ in shore sands of New Jersey;⁷ in the Ventimiglia Sands, Italy;⁸ in the limestone soils of the East Indian Archipelago.⁹

REMARKS.—Cordierite being of low specific gravity will occur in the light concentrate and may thus be easily confused with quartz or overlooked altogether. It is distinguished from the latter by its biaxial interference figure and by its pleochroism, if developed, and may be conveniently separated from quartz and feldspar by the electro-magnet. For a full and valuable discussion of cordierite in the Dartmoor detritals (much of which is applicable to other occurrences) see reference ⁵ below.

References.

- ¹ A. Gilligan, *Quart. Journ. Geol. Soc.*, 75, 1919, p. 251.
- ² A. Heard, *Geol. Mag.*, 59, 1922, p. 83.
- ³ H. H. Thomas, *Quart. Journ. Geol. Soc.*, 65, 1909, p. 234.
- ⁴ E. F. Davis, *Univ. California Publ., Bull. Dept. Geol. Sci.*, 11, 1918, p. 1.
- ⁵ A. Brammall, *Proc. Geol. Assoc.*, 39, 1928, p. 40.
- ⁶ A. Vendl, "Adatok a Duna Lomojanak astranytani ismertetesehez." 1910, Budapest.
- ⁷ R. J. Colony, *Journ. Sed. Pet.*, 2, 1932, p. 150.
- ⁸ I. Chelussi, *Boll. Soc. geol. ital.*, 31, 1912, p. 243.
- ⁹ J. van Baren, *Comm. Geol. Inst. Agric. Univ., Wageningen*, 14, 1928.

General References.

- H. H. Read, "On the Occurrence of Iron-Rich Cordierite in Aberdeenshire." *Geol. Mag.*, 67, 1930, p. 547.
- A. Brammall and B. R. Rao, "The Variable Composition of Cordierite in the Dartmoor Granites." *Mineral. Mag.*, 24, 1936, p. 221.

CORUNDUM [Pl. 17 A, facing p. 272.]

Chem. Comp. Al_2O_3 .

System. Trigonal.

Habit. Hexagonal bipyramidal. Rounded crystals. Twinned about (10 $\bar{1}$ 1), penetration and polysynthetic types known.

Structure. Granular.

Cleavage. None, but parting || (0001), rarely seen in small grains. Rhombohedral parting occurs due to twinning of (10 $\bar{1}$ 1).

Fracture. Conchoidal, uneven.

Hardness. 9.

Spec. Grav. 3.95-4.10.

Lustre. Adamantine, vitreous.

Colour. Frequently colourless or shades of blue (sapphire), red (ruby), or yellowish-brown.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. very high, $\epsilon = 1.760$, $\omega = 1.768$. Birefringence weak, $\omega - \epsilon = 0.008$. Optically uniaxial, negative. Sometimes optically anomalous, biaxial with axial angle up to 58°. Length fast. Straight extinction. Strongly coloured varieties are pleochroic, particularly sapphire: ϵ blue to ω bluish-green.

Characters in Sediments. Grains usually exhibit fracture and irregular outline. Less common are the basal flakes, determined by parting,

yielding good uniaxial figure. The colour is often unevenly distributed in the grains, some appearing very "blotchy." Such anomalous optical properties as may sometimes be noted are probably due to twinning.

Occurrence. In Silurian sediments near Melbourne, Australia (sapphire);¹ in the Pennant Sandstones, South Wales;² in the Coal Measures at Cwmgorse Valley, Wales;³ in Coal Measure shale at Cow Gate, Newcastle (sapphire);⁴ in the Durham Coal Measures;⁵ in the Kimmeridgian-Portlandian Sands, Buckinghamshire etc.;⁶ in the Portland Sand of Dorset;⁷ in the Ashdown Sand (Wealden), Hastings, Sussex;⁸ in the Sandgate Beds, Tilburstow Hill, Surrey;⁹ in the Greensand and Eocene deposits of the Haldon Hills, Devonshire;¹⁰ in the Pliocene of West Cornwall; in deposits of doubtful age at Marazion, Cornwall;¹¹ in gem sands of Brittany (sapphire);¹² in dune sands, Pointe de Grave (Landes) (sapphire);¹³ in the Beach Sands of New South Wales (sapphire);¹⁴ in surface deposits of S.E. Devonshire;¹⁵ in Dartmoor detritals;¹⁶ in sea-bottom deposits of the Gulf of Manaar.¹⁷

Possible Sources of Derivation. Igneous or metamorphic rocks, especially contact-metamorphosed limestones. Alluvial deposits.

REMARKS.—The combination of a high R.I., often blotchy colouring and low birefringence aids identification. Of sporadic occurrence in detrital sediments; colourless or yellow varieties are the most common. Sapphire, the blue variety, is on the whole rare; ruby, the red variety, not so far recorded (detrital) according to the author's observations. Take care to distinguish from adventitious "carborundum" which may have accidentally found its way into the heavy residue.

References.

- ¹ W. G. Langford, *Proc. Roy. Soc. Victoria*, 29, 1916, p. 40.
- ² A. Heard, *Geol. Mag.*, 60, 1923, p. 83.
- ³ A. Stuart, in D. F. Davies, E. Dix and A. E. Trueman, *South Wales Inst. Eng.*, 1928, p. 131.
- ⁴ S. Tomkeieff, *Proc. Geol. Assoc.*, 38, 1927, p. 518.
- ⁵ J. G. Kellett, *Proc. Univ. Durham Phil. Soc.*, 7, 1926, p. 208.
- ⁶ E. Neaverson, *Proc. Geol. Assoc.*, 36, 1925, p. 240.
- ⁷ M. P. Latter, *Proc. Geol. Assoc.*, 37, 1926, p. 73.
- ⁸ H. B. Milner, *Proc. Geol. Assoc.*, 36, 1925, p. 315.
- ⁹ G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915-16, p. 89.
- ¹⁰ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 79, 1923, p. 216, 226.
- ¹¹ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 79, 1923, p. 226.
- ¹² C. Barrois, *Ann. Soc. Geol. Nord.*, 24, 1896, p. 182.
- ¹³ R. Bréon, *Bull. Soc. franç. Min.*, 3, 1880, p. 45.
- ¹⁴ H. F. Whitworth, *Journ. Roy. Soc.*, New South Wales, 65, 1931, p. 59.
- ¹⁵ W. G. Shannon, *Geol. Mag.*, 64, 1927, p. 147.
- ¹⁶ A. Brammall, *Proc. Geol. Assoc.*, 39, 1928, p. 44.
- ¹⁷ J. Lomas, in W. H. Herdman, "Report on Pearl Oyster Fisheries of the Gulf of Manaar." *Roy. Soc.*, 1903.

General References.

- P. G. H. Boswell, "The Rarer Detrital Minerals of British Sedimentary Rocks." *Trans. Geol. Soc. Glasgow*, 18, 1926-7, p. 136.
- C. Raeburn and H. B. Milner, "Alluvial Prospecting." (Murby, London), 1927, p. 375 (for alluvial carborundum).
- A. E. Barlow, "Corundum, its Occurrence, Distribution, Exploitation and Uses." *Canada Dept. Mines. Geol. Surv. Mem.* 57, 1915.

A



A. CORUNDUM.

- 1, 3, 4. Miocene Sand, St. Keverne, Cornwall. [1, 1, x 60; 14, x 55]
2. Miocene Sand, Los Angeles, Calif., U.S.A. [x 50]

B



B. DIOPSIDE

1. Miocene Sand, Santa Fe Springs, Calif., U.S.A. [x 45]
2. Shore Sand, Kynance Cove, Cornwall. [x 45]
3. Shore Sand, Sproton, Yorks. [x 45]

C



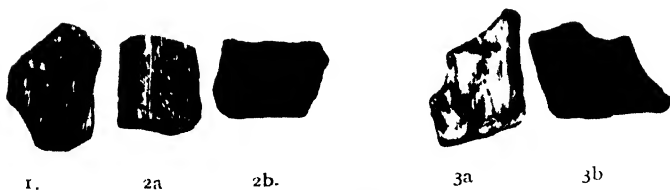
D



C, D. DOLOMITE

- C. Portland Sand, Dorset. [x 55]
D. River Sand, Tyrol. [x 25]

E



E. DIORMERITE.

1. Blue prismatic grain with vertical striations, Bridport Sand, West Bay, Dorset. [x 130]
2. Upper Greensand, Lulworth Cove, Dorset. [x 105] (a) Position of minimum absorption,
(b) Position of maximum absorption
3. Bagshot Beds, 3 mls. W. of Ringwood, Hants. [x 130] (a) and (b) as in 2 above
[1-3 Photos by A. W. GROVES]

CROSSITE

(AMPHIBOLE GROUP)

Chem. Comp. $\text{Na}_2\text{O} \cdot 4(\text{Mg}, \text{Fe})\text{O} \cdot (\text{Fe}, \text{Al})_2\text{O}_3 \cdot 8\text{SiO}_2$.

System. Monoclinic.

Habit. Prismatic.

Structure. Crystalline.

Cleavage. Perfect $\parallel (110)$ at 124° .

Fracture. Irregular.

Hardness. 6.

Spec. Grav. 3.16 .

Lustre. Dull, resinous.

Colour. Bluish black.

Mag. Prop. Moderately magnetic.

Elect. Prop. Poor conductor.

Opt. Prop. R.I. high, $\alpha = 1.65 \pm$, $\beta = ?$, $\gamma = 1.66 \pm$ (A. N. Winchell); $\beta = 1.670$ (E. S. Larsen). Birefringence moderate, $\gamma - \alpha = 0.01 \pm$ (A. N. Winchell). Optically biaxial, negative. Position of optic axial plane varies with composition, recorded both \parallel and $\perp (010)$. Oblique extinction. $Z \wedge c = 3^\circ$, $Z = b$, $Y \wedge c$, small to moderate. Optic axial angle variable. Dispersion very strong, $\rho > \nu$. Pleochroism strong, $X =$ bright yellow or colourless, $Y =$ deep blue, $Z =$ violet.

Characters in Sediments. A very rare mineral in detrital sediments, but to be anticipated where soda-bearing amphiboles are diagnosed. Similar form to glaucophane (q.v. p. 289), i.e. quite irregularly shaped grains determined by (110) cleavage and exhibiting characteristic colour and pleochroism.

Occurrence. In siliceous shale (of Miocene or Pliocene age), Southern California, U.S.A.;¹ in the San Onofre Breccia (Lower Miocene), California, U.S.A.²

Possible Sources of Derivation. Schist and contact metamorphic rocks.

REMARKS.—Crossite is a soda-bearing amphibole intermediate in composition between glaucophane (p. 289) and riebeckite (p. 333).

References

¹ R. D. Reed, *Journ. Geol.*, 36, 1928, p. 342.

² A. O. Woodford, *Univ. California Publ., Bull. Dept. Geol. Sci.*, 36, 1925, p. 159

CYMATOLITE

See Spodumene, p. 340.

DELESSITE

(CHLORITE GROUP)

Chem. Comp. $4(\text{Mg}, \text{Fe})\text{O} \cdot 2\text{Al}_2\text{O}_3 \cdot 4\text{SiO}_2 \cdot 5\text{H}_2\text{O}$.

System. Monoclinic.

Habit. Spherulitic, lamellar

Structure. Crystalline.

Cleavage. Good $\parallel (001)$.

Fracture. Irregular.

Hardness. 2.

Spec. Grav. $2.8 \pm$.

Lustre. Vitreous, dull.

Colour. Green, olive green, pink. Translucent.

Mag. Prop. Weakly magnetic.

Elect. Prop. Poor conductor.

Opt. Prop. R.I. high, $\alpha = 1.605$, $\beta = 1.619$, $\gamma = 1.619$. Birefringence moderate, $\gamma - \alpha = 0.014$. Optically biaxial, negative. Optic axial plane $\parallel (010)$. $Bxa = X \perp (001)$. $2V = 0^\circ \pm$: often pseudo-uniaxial. $X \wedge c = 0^\circ - 7^\circ$. Pleochroism distinctive: X = pale green, yellow, colourless, $Y = Z$ = green or pink.

Characters in Sediments. Delessite is probably a rare species in detrital sediments, though not necessarily so in parent rocks. Its lamellar or spherulitic forms are characteristic, otherwise it is in many properties similar to penninite (*q.v.* p. 323). It differs from this mineral in its negative sign and higher R.I. "Ultra-blue" anomalous interference colours rarely exhibited; more commonly delessite shows decided polarisation colours.

Occurrence. In certain deep sea deposits;¹ in the Sands of Dancalia, Africa.²

Possible Sources of Derivation. Amygdaloidal basalt; rock cavities of all kinds; alteration products resulting from hydrothermal action on ferro-magnesian minerals.

REMARKS.—Delessite is essentially a ferriferous penninite.

References.

¹ H.M.S. Challenger, Report on the scientific results of the voyage of 1891 (Admiralty).

² E. Artini, *Atti Soc. ital. Sci. nat.*, 60, 1921, p. 371.

DIALLAG

(VARIETY OF DIOPSIDE, *q.v.* p. 277.)

DIAMOND

Chem. Comp. C.

System. Isometric.

Habit. Octahedral, dodecahedral, tetrahedral and modified forms. Crystals often curved. Contact and penetration twins on (111), also on (001).

Structure. Crystalline.

Cleavage. Perfect $\parallel (111)$.

Fracture. Irregular, conchoidal. Brittle.

Hardness. 10.

Spec. Grav. 3.52.

Lustre. Adamantine to greasy.

Colour. Colourless, white, yellow, orange, red, green, blue, brown, black. Transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. very high, $n = 2.419$. Optically isotropic. Abnormally shows uniaxial interference figure and interference colours in bands or centred about inclusions; due to strain and noted in twin crystals.

Characters in Sediments. In clear, colourless octahedral grains with slight rounding of angles. Inclusions common, e.g. graphite, magnetite, iron ores, zircon, mica and gaseous. The deep coloured (brown and black) varieties are largely due to carbonaceous matter.

Occurrence. In alluvial sands, British Guiana;^{1, 2} in alluvial sands, South-West Africa;³ in alluvial sands, Gold Coast, West Africa;⁴ in alluvial sands, Somobula Forest, S. Rhodesia.⁵

Possible Sources of Derivation. Peridotite and associated ultrabasic rocks; quartzose conglomerates of suitable provenance; pegmatite veins; alluvial deposits; glacial drift.

REMARKS.—Rare in detrital sediments unless in environments including diamondiferous rocks. "Bort" is the spherical type with roughened surface, often radiating, fibrous structure; "Bywater" is the yellow variety; "Carbonade" is the black diamond, opaque, without cleavage, compact or massive.

References.

- ¹ L. T. Emory, *Eng. Min. Journ. Press*, 115, 1923, p. 571.
- ² L. J. Spencer, *Mineral. Mag.*, 20, 1924, p. 186.
- ³ J. W. Finch, *Eng. Min. Journ. Press*, 113, 1922, p. 317.
- ⁴ A. E. Kitson, *Govt. Gold Coast Accra, Rep. Geol. Surv.*, 1922-1923.
- ⁵ A. M. MacGregor, *S. Rhodesian Geol. Surv. Bull.* 8, 1923, p. 38.

General References.

- M. Bauer, "Precious Stones." (*Trans. L. J. Spencer*), 1904, p. 113.
 F. P. Mennell, "Note on the Colours of Some Alluvial Diamonds." *Mineral. Mag.*, 14, 1906, p. 202.
 W. Crook, "Diamonds." London, 1909.
 W. R. Cattelle, "The Diamond." New York, 1911.
 J. R. Sutton, "Diamond, a Descriptive Treatise." (Murby, London), 1928.

DIASPORE

Chem. Comp. $\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$. Also with Mn and Fe.

System. Orthorhombic.

Habit. Prismatic, flattened || (010); elongated || c.

Structure. Crystalline, massive.

Cleavage. Perfect || (010); distinct || (210).

Fracture. Uneven.

Hardness. 6.5-7.

Spec. Grav. 3.4-3.5.

Lustre. Pearly, dull.

Colour. White, grey, pink, red.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. high, $\alpha = 1.702$, $\beta = 1.722$, $\gamma = 1.750$. Birefringence strong, $\gamma - \alpha = 0.048$. Optically biaxial, positive. Optic axial plane || (010). $Bx = Z = a$. $X = c$. Straight extinction. $2V = 84^\circ$. Dispersion weak, $\rho < \nu$. Pleochroism noted in some examples, $X = Y =$ colourless, $Z =$ blue; or $X =$ violet or red brown, $Z =$ yellowish white.

Characters in Sediments. An uncommon species in detrital sediments, but where diagnosed, tends to grains of prismatic form, determined

largely by (010) cleavage, with uneven terminations. Characterised by colour, pleochroism, high R.I. and strong birefringence and optic axial plane || cleavage. To be anticipated in sediments containing bauxite and corundum.

Occurrence. In clays from various stratigraphical horizons of the Cambrian, Carboniferous and Upper Cretaceous, U.S.A.;¹ in the sands from Limero, Bahia, Brazil;² in the shore sands of the Adriatic coast;³ in the sands of the coast of Tuscany, Italy;⁴ in association with diamonds and carbonados in the state of Bahia, Brazil;⁵ in the sands of the Tyrrhenian coast, Italy.⁶

Possible Sources of Derivation. Volcanic rocks (with alunite); schists; bauxite deposits.

References.

- ¹ R. E. Somers, *Journ. Washington Acad. Sci.*, 9, 1919, p. 113.
- ² A. Damour, *Bull. Soc. géol. France*, 13, 1856, p. 542.
- ³ I. Ricciardi, *Atti Soc. ital. Sci. nat.*, 33, 1890, p. 41.
- ⁴ I. Chelussi, *Boll. Soc. geol. ital.*, 29, 1910, p. 207.
- ⁵ J. C. Branner, *Amer. Journ. Sci.*, 31, 1911, p. 480.
- ⁶ G. Uzielli, *Atti R. Accad. Lincei.*, 3, 1875-6, p. 862.

DICKITE

(KAOLINITE GROUP)

Chem. Comp. $\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$.

System. Monoclinic.

Habit. Hexagonal basal plates (001).

Structure. Crystalline, scaly.

Cleavage. Perfect || (001).

Fracture. Uneven.

Hardness. 2.

Spec. Grav. 2.6.

Lustre. Pearly, glistening.

Colour. White.

Mag. Prop. Non-magnetic.

Elect. Prop. ?

Opt. Prop. R.I. low, $\alpha = 1.561$, $\beta = 1.563$, $\gamma = 1.567$. Birefringence weak, $\gamma - \alpha = 0.006$. Optically biaxial, positive. Optic axial plane \perp (010). $Bxa = Z = b \perp$ (010). $Y \wedge a = 11^\circ - 16^\circ$. $X \wedge c = 15^\circ - 20^\circ$. $2V = 68^\circ - 80^\circ$. Dispersion strong, $\rho < \nu$.

Characters in Sediments. Generally occurs as very small hexagonal flakes, white in colour and with glistening lustre. Liable to be confused with kaolinite, but distinguished by position of Bxa and positive character which are different from the mineral (p. 302).

Occurrence. Coal Measure shale, Cow Gate, Newcastle;¹ certain clays and limestones, Columbia, Missouri, U.S.A.²

Possible Sources of Derivation. Ball clay, china clay and kaolinite-bearing clays.

References.

- ¹ S. Tomkeieff, *Proc. Geol. Assoc.*, 38, 1927, p. 518.
- ² W. A. Tarr and W. D. Keller, *Amer. Mineral.*, 21, 1936, p. 109.

DIOPSIDE [Pl. 17 B, facing p. 272.]

(PYROXENE GROUP)

Chem. Comp. CaO.MgO.2SiO₂.*System.* Monoclinic.*Habit.* Prismatic, more rarely tabular or bladed; sometimes twinned about (100) or (001).*Structure.* Crystalline.*Cleavage.* Always || (110); sometimes || (100), rarely || (010). Parting || (001) in twinned crystals. Parting on (100) well developed in diallage variety.*Fracture.* Uneven: often shown by irregular cracks traversing the crystal.*Hardness.* 5-6.*Spec. Grav.* 3.11-3.42.*Lustre.* Vitreous, sometimes resinous.*Colour.* Colourless, pale green, white or grey.*Mag. Prop.* Weakly magnetic.*Elect. Prop.* Moderate conductor.*Opt. Prop.* R.I. high, $\alpha = 1.664$, $\beta = 1.671$, $\gamma = 1.694$. Birefringence strong, $\gamma - \alpha = 0.030$. Optically biaxial, positive. $2V = 59^\circ$. Optic axial plane || (010). $Bxa = Z$ inclined at $38^\circ 30'$ to c axis (varies). Oblique extinction: angle 38° to 45° (measured from c in the plane (010)). $\sim Y || b$. Tabular grains || (100) give straight extinction || first cleavage. Slight dispersion of bisectrices: $\rho > \nu$. Non-pleochroic.*Characters in Sediments.* Detrital diopside is distinguished chiefly by its tendency to occur in colourless to grey or pale green grains, by its refractive index, high polarisation colours and oblique extinction angle (higher than kyanite, with which, in the absence of cleavage traces in that mineral, it is liable to confusion). Incipient alteration to a chlorite species, bastite, calcite and/or epidote may sometimes be noted. Inclusions of ilmenite, magnetite and apatite are not uncommon.*Occurrence.* In the Llandeilo sandstone of Glyn;¹ in the wind-blown sands of Pembrokeshire (Newgale);² in the dune sands of South Wales;³ in the shore sands of the Lizard, Cornwall;² sands and clays sampled from two borings in the plain of Lombardy, Northern Italy;⁴ various foreign Tertiary sands rich in pyroxene minerals;² in the coastal sands of Carnarvonshire;⁵ in beach sands of Cedar Point, Ohio, U.S.A.⁶*Possible Sources of Derivation.* Igneous rocks, especially of a basic type. Gneiss, schist and contact metamorphic rocks.**REMARKS.**—"Diallage" is a distinctive variety of diopside, characterised by prominent parting on (100) and usually "schillerisation," superficial interference effect due to formation of thin oxide or hydrate films in surface cracks (solution along parting planes). This property it shares with bronzite (p. 282), the orthorhombic pyroxene, but differs from that mineral in its oblique extinction. Diallage has a platy character, irregular outline, bronze-like lustre and is full of inclusions. In feriferous varieties it is pleochroic, $X = \text{green}$, $Y = \text{brown}$, $Z = \text{green}$. Detrital diallage should be looked for in recent sediments whose provenance is associated with basic rocks of a gabbro type, e.g. shore sands, Lizard district, Cornwall.*References.*¹ J. Lomas, *Proc. Geol. Assoc.*, 20, 1908, p. 477.² Author's observations.³ A. Stuart, *Proc. Geol. Assoc.*, 35, 1924, p. 324.⁴ I. Chelussi, *Boll. Soc. geol. ital.*, 43, 1924, p. 161.⁵ S. A. Billingshurst, *Geol. Mag.*, 66, 1929, p. 289.⁶ F. J. Pettijohn and J. D. Ridge, *Journ. Sed. Pet.*, 3, 1933, p. 92.

DOLOMITE [Pl. 17 C, D, facing p. 272.]

Chem. Comp. (Ca,Mg)CO₃.

System. Trigonal.

Habit. Simple rhombohedron (10 $\bar{1}$ 1) often curved; also irregular. Twinned about (01 $\bar{1}$ 2).

Structure. Crystalline, massive.

Cleavage. Perfect || unit rhombohedron (10 $\bar{1}$ 1). Parting || (01 $\bar{1}$ 2).

Fracture. Conchoidal, but seldom observed.

Hardness. 3.5-4.

Spec. Grav. 2.8-2.9.

Lustre. Vitreous, pearly.

Colour. Colourless, white, greenish-white, brown and reddish-brown. Transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low for ϵ , high for ω . $\omega = 1.681$, $\epsilon = 1.500$; ω and ϵ vary with amount of FeCO₃ present. (See *Ankerite*, p. 240.) Birefringence very strong, $\omega - \epsilon = 0.181$. Optically uniaxial, negative. Usually shows a partial figure. Non-pleochroic.

Characters in Sediments. Chiefly recognised as grains by simple rhombohedral habit (rare in calcite), characteristic "twinkling" (on rotation of polariser) and sometimes by its zoning; almost invariably of secondary origin, hence tends to exhibit its rhombohedral character conspicuously.

Occurrence. In the Silurian Rocks of Southern Scotland;¹ in Devonian limestones, Torquay district;² in the Trias of East Cheshire;³ in the Keuper Marls of Charnwood, Leicestershire;⁴ in the Portland Sand of Dorset;⁵ in the North Sea Drift (from Overstrand to Heydon), Norfolk;⁶ in the Dune Sands of South Wales;⁷ in river sands from the Ure and the Ouse.⁸

Possible Sources of Derivation. Derived dolomite is very rare, but if present is probably traceable to dolomitic limestone close at hand; in sediments is generally authigenic.

REMARKS.—Owing to its higher gravity than calcite, dolomite tends to come down with the "heavy" crop separated with bromoform. It is practically insoluble in cold hydrochloric acid, also in acetic acid, but is soluble in these reagents if warm. For differentiating tests from calcite, see p. 258. The variety "*Ankerite*" (q.v. p. 240) is characterised by the presence of iron replacing some of the magnesium.

References.

- ¹ W. Mackie, *Rep. Brit. Assoc.*, 1928 (Glasgow), 1929, p. 556.
- ² W. G. Shannon, *Proc. Geol. Assoc.*, 39, 1928, p. 150.
- ³ H. W. Greenwood, *Proc. Liverpool Geol. Soc.*, 12, 1920, p. 325.
- ⁴ T. O. Bosworth, "Keuper Marls Around Charnwood," *Leicester Lit. and Phil. Soc.*, 1913, p. 81. Also C. G. Cullis, *Rep. Brit. Assoc. for Adv. of Sci.*, Leicester, 1907, p. 506.
- ⁵ M. P. Latter, *Proc. Geol. Assoc.*, 37, 1926, p. 85.
- ⁶ P. G. H. Boswell, *Proc. Geol. Assoc.*, 27, 1916, p. 92.
- ⁷ A. Stuart, *Proc. Geol. Assoc.*, 35, 1924, p. 322.
- ⁸ S. Melmore, *Geol. Mag.*, 63, 1926, p. 268.

DUMORTIERITE

[Pl. 5, facing p. 172, and Pl. 17 E, facing p. 272.]

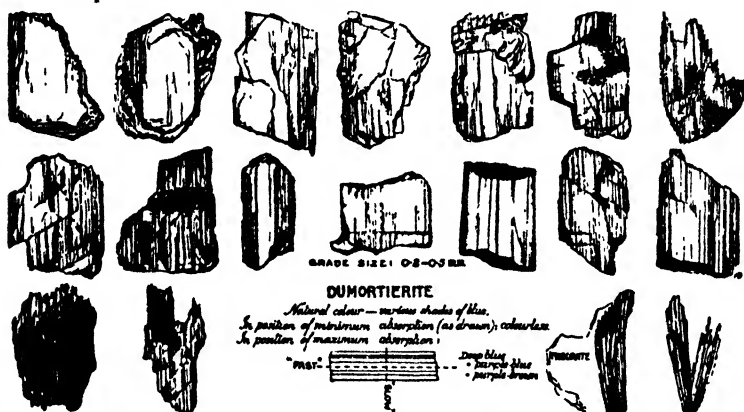
Chem. Comp. $8\text{Al}_2\text{O}_3 \cdot \text{B}_2\text{O}_3 \cdot 6\text{SiO}_2 \cdot \text{H}_2\text{O}$.**System.** Orthorhombic.**Habit.** Prismatic. Sometimes twinned about (110); also interpenetrated.**Structure.** Crystalline; or in fibrous or columnar aggregates.**Cleavage.** Good $\parallel (100)$, less distinct $\parallel (110)$. Parting observed $\parallel (001)$.**Fracture.** Uneven, but tends to coincide with parting planes.**Hardness.** 7.**Spec. Grav.** 3.26-3.36.**Lustre.** Vitreous.**Colour.** Colourless, greenish-blue, blue, grey, yellow-green, purple-grey, mauve. Transparent to translucent.**Mag. Prop.** Non-magnetic.**Elect. Prop.** Non-conductor.

FIG. 79. Dumortierite from Dartmoor Granite (A. Brammall).

Opt. Prop. R.I. high, $\alpha = 1.678$, $\beta = 1.686$, $\gamma = 1.689$. Birefringence moderate, $\gamma - \alpha = 0.011$. Optically biaxial, negative. $2V = 30^\circ - 40^\circ$. $2E = 52^\circ - 70^\circ$. Optic axial plane $\parallel (010)$. $Bxa = X \parallel c \perp (001)$. $Y \parallel b$, $Z \parallel a$. Straight extinction. Strong dispersion, $\rho > \nu$ or $\rho < \nu$. Pleochroism marked: $X = \text{deep blue}$, $Y = \text{yellow-violet}$, $Z = \text{colourless or green}$. Maximum absorption both with crystalline and fibrous varieties \parallel vibration direction of polariser (E-W).

Characters in Sediments. Presents unevenly terminated prismatic grains, sometimes with conspicuous striations \parallel prism edge. The resemblance to tourmaline is marked, especially in colour, but the refractive index of dumortierite is higher. Pleochroism is the chief diagnostic feature, the colour-change being very strong indeed, maximum absorption being as shown in Fig. 79 above. It is sometimes found as inclusions in cordierite (p. 270), when it is surrounded with pleochroic halos. Incipient alteration to muscovite is noted.

Occurrence. In the Bridport Sands (Inferior Oolite), West Bay, Dorset;¹ in Sandstone of the Weald Clay, Surrey;² in the Lower Greensand of the Dorking-Leith Hill district;³ in the Upper Greensand, Lulworth Cove, Dorset;⁴ in the Gault Clay, Lulworth Cove, Dorset;⁵ in the Blackheath Beds, Shirley, Surrey;⁶ in the Bagshot Beds of Bourne-

mouth, Hampshire;⁷ in the Bagshot Beds, Wimborne, Dorset;⁸ Late Tertiary-Quaternary Sands, San Joaquin Valley, California, U.S.A.;⁹ in the Eocene of Great Haldon, Devonshire.¹⁰

Possible Sources of Derivation. Granite pegmatite; gneiss; metamorphic rocks.

REMARKS.—A. W. Groves has pointed out that most of the dumortierite he has found in English sediments is of a "Stephens Ink" blue colour. In all cases the greatest care is necessary in diagnosis, implying accurate optical measurements, to prevent any possible confusion with blue tourmaline etc.

N.B.—Keen search for detrital dumortierite in British sediments has been made following the records published by A. W. Groves. The discovery by J. N. Montgomery of a grain in the Neolithic silts of Piltown, Sussex, is of particular interest. This example is colourless, with strong violet absorption, thus differing from H. A. Hayward's Wealden examples and from those found by A. W. Groves. The only known occurrence of similar dumortierite to that of the Piltown grain is in the Land's End granite, according to A. W. Groves' observations. Other records since the above are from the Lower Greensand, Aylesbury, Buckinghamshire, and from the Oligocene of Totland Bay, I.O.W., by G. C. Flower and M. H. Lowson respectively. (Royal School of Mines, London, 1928/29.)

References.

- ¹ A. W. Groves, *Mineral. Mag.*, 21, 1928, p. 489.
- ² H. A. Hayward, Recorded in H. B. Milner, "Supplement to Sedimentary Petrography." (Murby, London), 1926, p. 64; A. W. Groves, *op. cit.* p. 489.
- ³ H. A. Hayward, *Proc. Geol. Assoc.*, 43, 1932, p. 1.
- ^{4, 6-8} A. W. Groves, *op. cit.*
- ^{5, 10} A. W. Groves, personal communication.
- ⁹ R. D. Reed and J. P. Bailey, *Bull. Amer. Assoc. Petrol. Geol.*, 11, 1927, p. 363.

General References.

- P. G. H. Boswell, *Proc. Liverpool Geol. Soc.*, 13, 1923, p. 268.
 W. Mackie, "Dumortierite in British Rocks," *Trans. Edinburgh Geol. Soc.*, 11, 1925, p. 352.
 A. Brammell, "Dartmoor Detritals," *Proc. Geol. Assoc.*, 39, 1928, p. 43.
 W. Mackie, *Rep. Brit. Assoc.*, 1928 (Glasgow), 1929, p. 556.

ENIGMATITE

Chem. Comp. $2\text{Na}_2\text{O} \cdot 9\text{FeO} \cdot (\text{Al}, \text{Fe})_2\text{O}_3 \cdot 12(\text{Si}, \text{Ti})\text{O}_2$.

System. Triclinic.

Habit. Prismatic, vertically elongated. Twinning on (010), sometimes lamellar.

Structure. Crystalline.

Cleavage. Distinct || (110) and (1 $\bar{1}$ 0). Cleavage angle 114°.

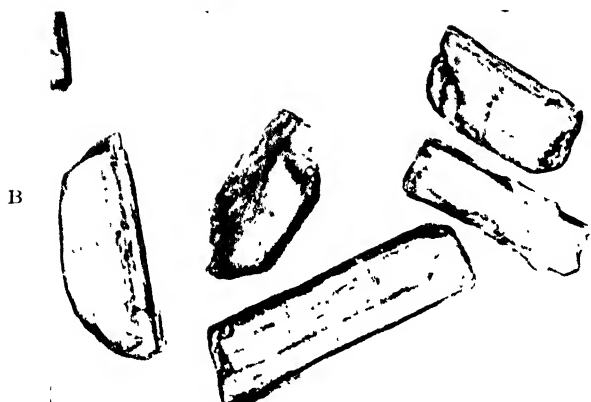
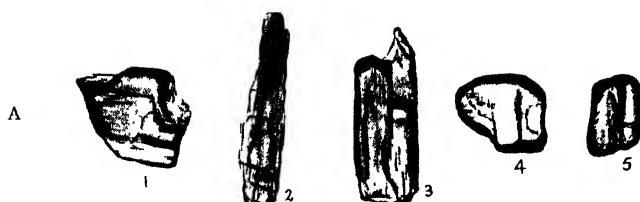
Fracture. Irregular.

Hardness. 5.5.

Spec. Grav. 3.74-3.85.

Lustre. Vitreous.

Colour. Black.



A, B, ENSTATITE.

- A 1-3. Shore Sand, Kynance, Cornwall [x 40]
 A 4. Shore Sand, Specton, Yorkshire [x 40]
 A 5. Blown Sand, Newgate, Pembrokeshire [x 40]
 B. Shore Sand, Cornwall [x 48]



C, D. EPIDOTE.

- C. Eocene, Virginia, U.S.A. [x 38]
 D. Shore Sand, Galway [x 62]

Mag. Prop. Moderately magnetic.

Elect. Prop. Moderate conductor.

Opt. Prop. R.I. very high, $\beta = 1.80$. Birefringence weak, $\gamma - \alpha = 0.006$. Optically biaxial, positive. Optic axial plane nearly $\parallel (010)$. $Bxa = Z$ inclined at 45° to c and 4° to (100) . Y near b . Length of prism fast. $2V = 32^\circ$. $2E = 59^\circ$. Dispersion $\rho < \nu$? Intensely pleochroic, $X =$ reddish brown $< Y =$ dark brown $< Z =$ very dark brown.

Characters in Sediments. Diagnosed chiefly by its intense brown or brownish black colour, high relief, oblique extinction (4° to prismatic cleavage) and strong, distinctive pleochroism.

Occurrence. Dune sands, S. Wales.¹

Possible Sources of Derivation. Nepheline-syenites and allied rocks.

REMARKS.—Enigmatite is a rare species and to be anticipated in sediments only where alkaline petrographic provinces are laid under contribution. A closely allied species is "*rhænite*," where the alkali is reduced to a minimum; it has similar properties to enigmatite and is normally found in basic igneous rocks.

Reference.

¹ A. Stuart, *Proc. Geol. Assoc.*, 35, 1924, p. 325.

General Reference.

C. Palache, "Crystallographic Notes on Anapaite, Ainigmatite and Eudidymite." *Zeitschr. für Kristallographie (A)*, Band 86, Heft 3/4, 1933, p. 280.

ENSTATITE

(PYROXENE GROUP)

[Pl. 18 A, B, facing p. 281.]

Chem. Comp. $MgSiO_3$.

System. Orthorhombic.

Habit. Prismatic, bipyramidal. Twinning rare on (014) or (101) .

Structure. Crystalline.

Cleavage. Good $\parallel (110)$ at 88° . Parting on (010) , (100) , rarely (001) .

Fracture. Uneven.

Hardness. 5-6.

Spec. Grav. 3.1-3.3.

Lustre. Vitreous to pearly; dull submetallic (bronze-like) in *bronzite*.

Colour. Grey, yellow, greenish-white or olive green. Transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. high, $\alpha = 1.650$, $\beta = 1.653$, $\gamma = 1.658$. Birefringence weak, $\gamma - \alpha = 0.008$. Optically biaxial, positive. Optic axial plane $\parallel (010)$. Length slow. $Bxa = Z \perp (001)$. Straight extinction. $2V = 70^\circ$. $X \parallel a$ fast, $Y \parallel b$, $Z \parallel c$ slow. Optic axial dispersion slight: $\rho < \nu$. Pleochroism faint in the normal mineral (thick grains), stronger with increase of iron; $X =$ yellow, $Y =$ brownish-yellow, $Z =$ green; distinctive for hypersthene (*q.v.*). *Bronzite* is an iron-bearing enstatite with optical properties intermediate between those of enstatite and hypersthene.

Characters in Sediments. Enstatite occurs in irregular or prismatic grains characterised by a somewhat "dirty" colour, vitreous or pearly lustre of cleavage flakes (most grains tend to be (110) flakes), straight extinction, high refractive index and low birefringence (lower than hypersthene); also by its lack of pleochroism (in thin grains), which, together with its positive sign, serves to distinguish it from that mineral. Inclusions of magnetite, apatite or zircon are common, while alteration to a fibrous or lamellar aggregate (*bastite*) is not uncommon. The submetallic lustre acquired by cleavage flakes of enstatite, together with the bronze colour, are due to internal decomposition, whereby oxide of iron tends to occupy cleavage cracks producing the characteristic "Schiller-spath" or Schiller-structure, by which properties *bronzite* is diagnosed; further alteration to chlorite minerals frequently observed in detrital bronzite.

Occurrence. Silurian Rocks of Southern Scotland;¹ Middle and Upper Old Red Sandstone of Scotland;² North Sea drift and Upper Glacial Brick-earth, East Anglia;³ shore sand of Kynance Cove and other places, Lizard, Cornwall; ⁴ coastal sands of Carnarvonshire; ⁵ various foreign alluvial deposits, soils etc.⁶

Possible Sources of Derivation. Basic and ultrabasic igneous rocks; less commonly metamorphosed sedimentary rocks.

REMARKS.—It should be noted that pure enstatite is non-magnetic and can therefore be separated from hypersthene by electro-magnetic treatment. The mineral is not attacked by hydrochloric acid, but hypersthene is less stable in this respect. "Bastite" often develops as a pseudomorph after enstatite whereby the perfect (001) cleavage of antigorite, p. 242 (of which bastite is but a coarse variety) is made parallel to the (010) parting of enstatite.

References.

- ¹ W. Mackie, *Rep. Brit. Assoc.*, 1928 (Glasgow), 1929, p. 556.
- ² W. Mackie, *Trans. Edinburgh Geol. Soc.*, 11, 1923, p. 138.
- ³ P. G. H. Boswell, *Proc. Geol. Assoc.*, 27, 1916, p. 79.
- ⁴ Author's observations.
- ⁵ S. A. Billingham, *Geol. Mag.*, 66, 1929, p. 289.
- ⁶ E. Tacconi, *Rend. R. Ist. lombardo*, 34, 1901, p. 873.

EPIDOTE (Pistacite)

(EPIDOTE GROUP)

[Pl. 18 C, D, facing p. 281.]

Chem. Comp. $4\text{CaO} \cdot 3(\text{Al}, \text{Fe})_2\text{O}_3 \cdot 6\text{SiO}_2 \cdot \text{H}_2\text{O}$.

System. Monoclinic.

Habit. Prismatic. Elongated || b with dissimilar terminations. Often striated || b. Frequently twinned about (100), rarely on (001).

Structure. Crystalline, fibrous, massive.

Cleavage. Perfect basal || (001). Imperfect || (100).

Fracture. Uneven.

Hardness. 6-7.

Spec. Grav. 3.25-3.5.

Lustre. Vitreous, sometimes resinous.

Colour. Greenish-yellow, dark green, shades of brown, grey.

Mag. Prop. Weakly magnetic.

Elect. Prop. Poor conductor.

Opt. Prop. R.I. high, $\alpha=1.722$, $\beta=1.742$, $\gamma=1.750$. Birefringence strong, $\gamma-\alpha=0.028$. Optically biaxial, negative. Optic axial plane $\parallel (010) \perp$ principal cleavage. $Bxa=X$ inclined at $0^\circ-5^\circ$ to c. $Y \parallel b$. $2V \approx 92^\circ$ (varies with amount of Fe_2O_3 present). Pleochroism weak: $Y=\text{greenish-yellow} > Z=\text{colourless} > X=\text{colourless, pale green, noticeable in thick grains. Strong dispersion, } \rho > v$.

Characters in Sediments. Irregular and rather angular grains common, the flattened "platy" forms often exhibiting partial (compass-needle) interference figure, due to emergence of one optic axis. Pale yellowish-green subangular grains, like small chips of broken "bottle-glass," are very characteristic of many sands and are remarkable for their transparency. A further diagnostic feature is the brilliant green-purple-red (ringed) interference tints observed in most clear individuals.

Occurrence. In the Old Red Sandstone of the West Midlands;¹ in the Permian Rocks of the Torquay Promontory;² in the Upper Lias—Lower Inferior Oolite of the West of England;³ in the Northampton Ironstone;⁴ in the Sandgate Beds of Surrey;⁵ in the Upper Greensand of Surrey;⁶ in Eocene and Oligocene sands of the Haldon Hills and Bovey Tracy respectively, Devonshire;⁷ in the Bagshot Beds of Essex;⁸ in Miocene-Pliocene sands of California⁹ (some of the Pliocene oil-sands of the Los Angeles Basin are particularly rich in epidote¹⁰); in the Pliocene deposits of West Cornwall;¹¹ in the later Tertiary deposits of East England;¹² in surface deposits of S.E. Devonshire;¹³ in dune sands of South Wales;¹⁴ in blown sands, New-gale, Pembrokeshire.¹⁵

Possible Sources of Derivation. Crystalline metamorphic rocks, especially altered impure limestones. Also from highly altered igneous rocks originally rich in ferro-magnesian minerals.

REMARKS.—In certain local environments, involving crystalline schists, amphibolites etc., as contributors to sedimentary deposits, detrital zoisite (p. 356) (the orthorhombic member of the epidote group) may be met with; detrital clinozoisite is also known in sediments (p. 269).

References.

- ¹ W. F. Fleet, *Geol. Mag.*, 63, 1926, p. 513.
- ² W. G. Shannon, *Proc. Geol. Assoc.*, 38, 1927, p. 135.
- ³ P. G. H. Boswell, *Geol. Mag.*, 61, 1924, p. 262.
- ⁴ J. G. A. Skerl, *Proc. Geol. Assoc.*, 38, 1927, p. 383.
- ⁵, ⁶ G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915-16, p. 84.
- ⁷ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 79, 1923, p. 226.
- ⁸ S. W. Wooldridge, *Proc. Geol. Assoc.*, 35, 1924, p. 376.
- ⁹ R. D. Reed and J. P. Bailey, *Bull. Amer. Assoc. Petrol. Geol.*, 11, 1927, p. 359.
- ¹⁰ Author's observations.
- ¹¹ H. B. Milner, *Quart. Journ. Geol. Soc.*, 78, 1922, p. 361.
- ¹² I. S. Double, *Proc. Geol. Assoc.*, 35, 1924, p. 340.
- ¹³ W. G. Shannon, *Geol. Mag.*, 64, 1927, p. 147, 149.
- ¹⁴ A. Stuart, *Proc. Geol. Assoc.*, 35, 1924, p. 324.
- ¹⁵ Author's observations.

General Reference.

- M. L. Goldman, *Amer. Journ. Sci.*, 39, 1915, p. 277 (for significance of scarce epidote in sediments, as exemplified by the Catahoula Sandstone of Texas).

FAYALITE

(OLIVINE GROUP)

Chem. Comp. $2\text{FeO}, \text{SiO}_2$.

System. Orthorhombic.

Habit. Prismatic, tabular \parallel (100). Twinning rare on (011).

Structure. Crystalline.

Cleavage. Distinct \parallel (010), indifferent \parallel (100).

Fracture. Irregular.

Hardness. 6.5.

Spec. Grav. 4.3.

Lustre. Vitreous.

Colour. Pale greenish yellow. Transparent to translucent.

Mag. Prop. Weakly magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. very high, $\alpha = 1.835$, $\beta = 1.877$, $\gamma = 1.886$. Birefringence strong, $\gamma - \alpha = 0.051$. Interference tints sometimes abnormal "blues and yellows." Optically biaxial, negative. Optical axial plane \parallel (001). $Bxa = X \perp$ (010) = b. $Z = a$. Straight extinction \parallel prism and principal cleavage. $2V = 47^\circ - 50^\circ$. Dispersion strong, $\rho > v$. Weakly pleochroic in some examples, $Y = \text{orange yellow} > X = \text{greenish yellow} > Z = \text{greenish yellow}$.

Characters in Sediments. Detrital fayalite is rare in sediments. It tends to the general irregular form of grain characteristic of olivine, but possesses stronger relief (higher R.I.), stronger birefringence (especially when abnormal blue and yellow tints are revealed) than does that species. Alteration to hematite, limonite or goethite along cleavage lines is noted, less commonly to antigorite (p. 242) when magnesium is present.

Occurrence. In Pennsylvanian and Devonian Sandstones, Mid-Continent, U.S.A.¹

Possible Sources of Derivation. Volcanic rocks, certain pegmatites; metallurgical slag.

Reference.

- ¹ F. C. Edson, *Rep. Cmmtte. Sedimentation* 1928-1929, No. 92, National Research Council, U.S.A., 1930, p. 70.

FLINT

See Chalcedony, p. 261.

FLUORITE [Pl. 19 A, B, facing p. 288.]

Chem. Comp. CaF_2 .

System. Isometric.

Habit. Either simple or modified cube; octahedral, dodecahedral; interpenetrant twins common about (111).

Structure. Crystalline, compact, massive.

Cleavage. Perfect \parallel (111).

Fracture. Conchoidal.

Hardness. 4.

Spec. Grav. 3.18.

Lustre. Vitreous.

Colour. Commonly colourless, white, green, blue or purple; also pink, brown and intermediate shades. Transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low. $n = 1.434$. Optically isotropic. May show anomalous polarisation due to internal strain.

Characters in Sediments. Frequently occurs as octahedral cleavage fragments, subangular or irregular. Rounded grains rare. Triangular plates with modified edges sometimes found. Detrital grains of this mineral are often violet in colour, though the colouring matter may not permeate the whole grain, thus rendering it "blotchy." Inclusions of iron-ores, manganese, hydrocarbon (?) or fluid. Diagnosed by its octahedral tendency, prominent relief and lower R.I. than Canada balsam, also by its isotropism.

Occurrence. In the Old Red Sandstone, Cardiff;¹ in the Carboniferous Limestone, Matlock district, Derbyshire (see p. 545);² in the Lower Carboniferous Sandstone, Cumberland;³ in the Bunter Pebble Bed, West of England;⁴ in the New Red Sandstone, West of England;⁵ in Dartmoor detritals;⁶ in shore sand, St. Ives Bay, Cornwall;⁷ in Red River sand, Camborne, Cornwall;⁸ prolific in shore sand at Down-derry, near Looe, Cornwall.⁸

Possible Sources of Derivation. Acid igneous rocks, metamorphic rocks and metalliferous veins. Also limestones.

References.

¹ A. Heard and R. Davies, *Quart. Journ. Geol. Soc.*, 35, 1924, p. 489.

² Author's observations.

³ H. P. Lewis, *Geol. Mag.*, 68, 1931, p. 543.

⁴ H. H. Thomas, *Quart. Journ. Geol. Soc.*, 58, 1902, p. 620.

⁵ H. H. Thomas, *Quart. Journ. Geol. Soc.*, 65, 1909, p. 231.

⁶ A. Brammall, *Proc. Geol. Assoc.*, 39, 1928, p. 37.

⁷ T. Crook and G. M. Davies, *Geol. Mag.*, 1909, p. 122.

⁸ Author's observations.

General Reference.

J. Drugman, "Different Habits of Fluorite Crystals." *Mineral Mag.*, 23, 1932, p. 137.

FUCHSITE

(MICA GROUP)

Chem. Comp. Chromium mica, Cr_2O_3 replacing part Al_2O_3 .

System. Monoclinic.

Habit. Platy || (001).

Structure. Crystalline, laminated.

Cleavage. Perfect || (001).

Fracture. Irregular.

Hardness. 2.5.

Spec. Grav. 2.86.

Lustre. Pearly.

Colour. Green. Translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low, $\beta = 1.594$. Birefringence strong, $\gamma - \alpha = 0.04$. Optically biaxial, negative. $Bxa = X \parallel c$. $2V = 40^\circ$. $2E = 66^\circ$. Basal cleavage plates yield good biaxial interference figure. Dispersion strong, $\rho > v$. Pleochroism, noted in thick grains, X = colourless or pale blue, Y = yellowish green, Z = dark bluish green.

Characters in Sediments. Fuchsite, the chromium mica, is rare in sediments, but where diagnosed is distinguished by its micaceous habit, green colour and pleochroism.

Occurrence. At the base of the San Onofre Breccia (Lower Miocene), California, U.S.A.;¹ in soils from Western Australia.²

Possible Sources of Derivation. Micaceous quartzite; mica schist; less commonly in gneiss and dolomite.

References.

¹ A. O. Woodford, *Univ. California Publ., Bull. Dept. Geol. Sci.*, 15, 1925, p. 159.

² D. Carroll, *Geol. Mag.*, 73, 1936, p. 503.

GALENA

Chem. Comp. PbS.

System. Isometric.



FIG. 80. Galena from Triassic Sandstone, Alderley Edge, Cheshire. [x 50.]

Habit. Cube, octahedron or combination of both.

Structure. Crystalline or massive.

Cleavage. Perfect $\parallel (100)$.

Fracture. Even.

Hardness. 2.5-2.75.

Spec. Grav. 7.4-7.6.

Lustre. Metallic.

Colour. Lead-grey. Opaque. Grey to white in vertical reflected light.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Characters in Sediments. Detrital galena is characterised by its colour, lustre, cubic form (usually cleavage) or by its occurrence as small, shapeless particles of typical lead-grey metallic lustre. With large grains, a black or blue superficial tarnish or white, powdery en-

crustation (cerussite, PbCO_3) may be noted. It is not a common constituent of sediments unless authigenic or locally where sulphide veins have contributed to sedimentary deposits.

Occurrence. Old Red Sandstone beneath London (Richmond boring, 1882);¹ in the Triassic Sandstones of Alderley Edge, Cheshire;² in the Fuller's earth (Aptian) of Redhill, Surrey;³ also of Nutfield, Surrey.⁴

Possible Sources of Derivation. Veins and beds in limestones; metallic sulphides with quartz or other gangue material; silver-lead ores; rarely in gneiss, granite-pegmatite etc.

References.

¹ J. W. Judd, *Quart. Journ. Geol. Soc.*, 40, 1884, p. 749.

² Author's observation. (N.B.—Much of this material is clearly an impregnation product, i.e. authigenic). See also A. Holmes, "Petrographic Methods." (Murby, London), p. 191.

³ G. M. Davies, *Proc. and Trans. Croydon Nat. Hist. Soc.*, 1915-16, p. 86.

⁴ E. F. Newton, *Proc. Geol. Assoc.*, 48, 1937, p. 181.

GARNET

See varieties:—

Almandite (p. 233).

Andradite (p. 238).

Grossularite (p. 292).

Melanite (p. 312).

Pyrope (p. 329).

Spessartite (p. 338).

Uvarovite (p. 350).

GASTALDITE

See Glaucophane, p. 289.

GIBBSITE (Hydrargillite)

Chem. Comp. $\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$.

System. Monoclinic.

Habit. Hexagonal basal tablets, lamellar.

Structure. Crystalline, massive, concretionary.

Cleavage. Perfect $\parallel (001)$ giving laminæ-like mica.

Fracture. Uneven.

Hardness. 3.

Spec. Grav. 2.35.

Lustre. Porcellanous, dull.

Colour. White, grey, green. Translucent to opaque.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low, $\alpha = 1.566$, $\beta = 1.566$, $\gamma = 1.587$. Birefringence moderate, $\gamma - \alpha = 0.021$. Optically biaxial, positive. Optic axial plane $\perp (001)$. $Bxa = Z$ inclined at $21^\circ - 44^\circ$ to c ; Y or $X = b$. $2V = 0^\circ - 40^\circ$ (variable). Dispersion strong, $\rho > \nu$ or $\rho < \nu$. Non-pleochroic.

Characters in Sediments. Occurs as tabular grains of pseudo-hexagonal

shape flattened || (001) or in irregular forms. It is probably authigenic in most instances in sediments. Liable to confusion with kaolinite (p. 302) and muscovite (p. 316); it has a higher birefringence than the former and a different sign from the latter.

Occurrence. In the Karstland bauxite;¹ in the residual clays of the Eastern United States.²

Possible Sources of Derivation. Bauxite deposits. Felspar (by decomposition).

References.

¹ M. Kispatic, *N.J.f. Min.*, B.-Bd., 34, 1912, p. 513.

² H. Ries, W. S. Bailey and others, *U.S. Geol. Surv. Bull.* 708, 1922.

GLAUCONITE [Pl. 19 c, facing p. 288.]

Chem. Comp. $\text{SiO}_2, \text{Al}_2\text{O}_3, \text{Fe}_2\text{O}_3, \text{FeO}, \text{MgO}, \text{K}_2\text{O}, \text{H}_2\text{O}$;

$\text{KMg}(\text{Fe}, \text{Al})_3\text{Si}_4\text{O}_{18} \cdot 3\text{H}_2\text{O}$ (A. N. Winchell).

System. Monoclinic.

Habit. Microcrystalline, laminated, platy; appears amorphous.

Structure. Granular, irregular. Organic structures common.

Cleavage. Perfect || (001).

Fracture. Uneven.

Hardness. 2.

Spec. Grav. 2.2-2.8.

Lustre. Dull, sometimes vitreous.

Colour. Various shades of green, olive green, blackish green, blackish yellow. Brown when altered. Translucent.

Mag. Prop. Moderately magnetic.

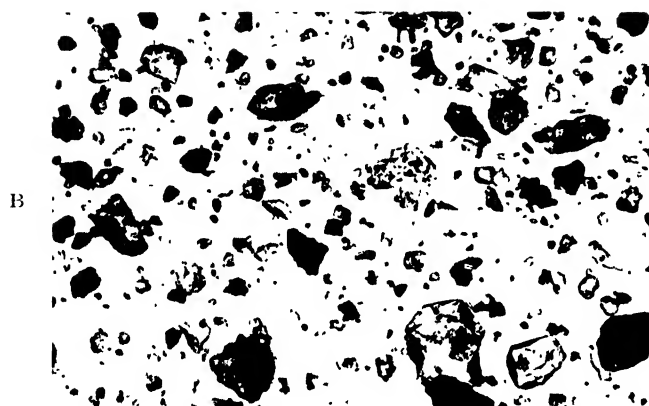
Elect. Prop. Non-conductor.

Opt. Prop. R.I. high, variable: $\alpha = 1.590-1.612$, $\beta = 1.609-1.643$, $\gamma = 1.610-1.644$ (A. N. Winchell quoting C. S. Ross). Birefringence moderate, $\gamma - \alpha = 0.018-0.032$. Optically biaxial, negative. $Bxa = X$ nearly \perp (001) cleavage. $2V = 0^\circ-20^\circ$. $2E = 33^\circ \pm$. Dispersion $\rho > v$. Pleochroism: X = straw yellow or pale yellow green $< Y = Z$ = green to yellowish green; or X = dark bluish green, Y and Z = lemon yellow.

Characters in Sediments. Rounded or irregular grains or aggregates, usually characteristic of the "light" material of certain sediments. Under high power magnification and with polarised light, distinct optical properties (as above) may be discerned. Frequently occurs as casts of *foraminifera*. Commonly dark green in colour, if not altogether opaque; strong tendency to show decomposition to limonite.

Occurrence. In the Cambrian, Ordovician, Silurian, Old Red Sandstone of the Midlands;¹ in the Upper Lias-Lower Inferior Oolite of the West of England;² Lower Greensand (especially the Sandgate Beds) of the Weald;³ in the Gault, Upper Greensand and Lower Chalk of Surrey;⁴ in the Upper Greensand of the Weymouth district, Dorset;⁵ in the Greensand of the Haldon Hills, Devonshire;⁶ in the Thanet Beds, Reading Beds and London Clay of the N.E. part of the London Basin;⁷ detrital glauconite in the Oligocene beds of Bovey Tracey, Devonshire;⁸ in the Bagshot Beds of Essex;⁹ in the Pliocene deposits of West Cornwall;¹⁰ in the later Tertiary deposits of the East of England;¹¹ in various valley gravels and loams of Surrey and the London district.¹²

Possible Sources of Derivation. Sedimentary rocks, more rarely from amygdaloidal lavas. Frequently of organic origin.



A, B FLUORITE.

A 1-4 Red River Sand, Cornwall [X 40]

B Carboniferous Limestone, Matlock, Derbyshire [X 64]



C. GLAUCONITE.

Casts of *Foraminifera*, Upper Greensand, Chaldon Herring, Dorset [X 50.]

REMARKS.—Glauconite is a mineral of considerable mineralogical and geological interest. It was for a long time supposed to be amorphous, but recent researches have shown this view to be untenable, since the "amorphous" granules so often described from sediments have in many cases been proved to be made up of laminæ having specific optical properties referable to monoclinic crystals. Glauconite occurs in abundance at certain stratigraphical horizons, especially in the Cretaceous Greensands. Its properties vary largely with amount of iron present, this factor affecting the S.G., which in some cases is >2.80 . Most varieties are decomposed by HCl, hence in preliminary treatment of samples with this acid much of the glauconite may be lost. Its prolific occurrence in the Greensands would seem to be a function of its chemical stability in this instance, rather than of accentuated development at that epoch. There is no reason to suppose that it was initially less common in older than in younger sediments; on the contrary, its characters frequently suggest derivation and redeposition from pre-existing deposits.* (See particularly p. 507 of this volume, references there cited, also paper by A. F. Hallimond (below).)

References.

- ¹ W. F. Fleet, *Geol. Mag.*, 62, 1925, p. 101, 102, 104, 106, 126.
- ² P. G. H. Boswell, *Geol. Mag.*, 61, 1924, p. 257, 258, 262.
- ^{3, 4} G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915-16, p. 82, 92.
- ⁵ Author's observations.
- ⁶ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 79, 1923, p. 209, 226.
- ⁷ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 71, 1915, table iv and p. 557, 580.
- ⁸ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 79, 1923, p. 218, 220.
- ⁹ S. W. Wooldridge, *Proc. Geol. Assoc.*, 35, 1924, p. 364, 376.
- ¹⁰ H. B. Milner, *Quart. Journ. Geol. Soc.*, 78, 1922, p. 348.
- ¹¹ I. S. Double, *Proc. Geol. Assoc.*, 35, 1924, p. 342.
- ¹² G. M. Davies, *op. cit.*, p. 78.

General References.

- *P. G. H. Boswell, "The Application of Petrographical and Quantitative Methods to Stratigraphy." *Geol. Mag.*, 1916, p. 107 etc.
 A. F. Hallimond, *Mineral. Mag.*, 19, 1922, p. 330.
 F. W. Clark, "The Data of Geochemistry." *U.S. Geol. Surv., Bull.* 770, 1924, p. 137, 510, 584.
 H. Schneider, *Journ. Geol.*, 35, 1927, p. 289.
 C. S. Ross, *U.S. National Mus. Proc.*, 19, 1926, No. 2.
 E. W. Galliher, "Glauconite Genesis." *Bull. Geol. Soc. Amer.*, 46, 1935, p. 1351.

GLAUCOPHANE

(AMPHIBOLE GROUP) [Pl. 20 C, facing p. 297.]

Chem. Comp. $\text{Na}_2\text{O} \cdot 2(\text{Fe}, \text{Ca}, \text{Mg})\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2?$

System. Monoclinic.

Habit. Prismatic, short "stumpy" crystals.

Structure. Crystalline.

Cleavage. Perfect || (110).

Fracture. Uneven.

Hardness. 6.

Spec. Grav. 3.3-3.15.

Lustre. Vitreous, pearly on cleavage fragments.

Colour. Colourless, pale blue, lavender blue to bluish-black.

Mag. Prop. Moderately magnetic.

Elect. Prop. Moderate conductor.

Opt. Prop. R.I. high, $\alpha=1.621$, $\beta=1.638$, $\gamma=1.638$. Birefringence moderate, $\gamma-\alpha=0.017$. Optically biaxial, negative. Optic axial plane \parallel (010). $Bxa=X$. $Y \parallel b$, $Z \wedge c=5^\circ \pm$. Oblique extinction, $3^\circ-11^\circ$, rarely $16^\circ-22^\circ$ in partially altered forms. Sometimes fails to extinguish in any position. Length and cleavage direction slow. $2V=45^\circ \pm$. $2E=77^\circ$. Pleochroism very marked, $Z=\text{blue}$, $Y=\text{lavender or violet}$, $X=\text{colourless to yellow or yellow-green}$. Dispersion strong, $\rho > \nu$.

Characters in Sediments. Commonly occurs as irregular grains with tendency to elongation in direction of the principal crystallographic axis (prismatic) and may or may not exhibit the characteristic pleochroism by which this species is invariably diagnosed. Many grains are undoubtedly derived by (110) cleavage. Another type is ragged in appearance, not unlike some varieties of tremolite or (save the colour) actinolite. Striae \parallel principal axis occasionally observed. Inclusions are usually common, e.g. magnetite, rutile, ? titanite, apatite.

Occurrence. In the Upper Lias—Lower Inferior Oolite of the West of England;¹ in the Northampton Ironstone;² in Lias—Inferior Oolite of the Midlands;³ in the Kimmeridgian-Portlandian sands of the South of England;⁴ in the Ashdown Sand (Wealden) of Hastings, Sussex;⁵ in the Oldhaven and Reading Beds of the London Basin;⁶ in Glacial Deposits of East Anglia;⁷ in wind-blown deposits of Guernsey;⁸ in blown sands from Newgale, Pembrokeshire;⁹ in sands of pre-glacial scree in Anglesey;¹⁰ also shore sands of that island;¹¹ in valley deposits in Surrey.¹²

Possible Sources of Derivation. Metamorphic rocks, especially schistose types; eclogites. Crystalline limestones.

REMARKS.—The more thorough searching of sediments in recent years has brought to light the widespread occurrence of this interesting mineral and, although seldom common in any one deposit, it has been shown by different investigators to occur consistently at certain horizons over large areas. In the author's experience it is especially prevalent in Miocene sediments (a coincidence) in countries as far removed as Trinidad, Venezuela, California, Italy and Iraq. In this respect it achieves the same distinction that andalusite has in connexion with its occurrence in Pliocene deposits (p. 237). P. G. H. Boswell remarks on the frequent association of glaucophane and chloritoid.³

Closely related to glaucophane is "gastaldite," an anhydrous, soda-bearing amphibole, having similar properties to glaucophane, but distinguished by its stronger birefringence and weaker dispersion.

Records of gastaldite are as follows:—in the Miocene sandstones of central Italy;¹³ in sea bed deposits in an area ranging from Corsica and Sardinia to Sicily;¹⁴ in the Ravenna sands, Italy;¹⁵ in the sand of San-sego, a small island off Quarnero.¹⁶

References.

- ¹ P. G. H. Boswell, *Geol. Mag.*, 61, 1924, p. 256.
- ² J. G. A. Skerl, *Proc. Geol. Assoc.*, 38, 1927, p. 383.
- ³ P. G. H. Boswell, *Trans. Geol. Soc. Glasgow*, 18, 1926-27, p. 139.
- ⁴ E. Neaverson, *Proc. Geol. Assoc.*, 36, 1925, p. 250.
- ⁵ H. B. Milner, *Proc. Geol. Assoc.*, 36, 1925, p. 315.
- ^{6, 8, 10, 12} P. G. H. Boswell, *op. cit.* (1926-27).
- ^{9, 11} Author's observations.
- ¹³ I. Chelussi, *Boll. Soc. geol. ital.*, 27, 1908, p. 251.
- ¹⁴ F. Salmoiraghi, *Rend. R. Ist. lomb.*, 43, 1910, p. 432.
- ¹⁵ I. Chelussi, *Boll. Soc. geol. ital.*, 30, 1911, p. 183.
- ¹⁶ F. Salmoiraghi, *Rend. R. Ist. lomb.*, 40, 1907, p. 870.

GOETHITE

Chem. Comp. $\text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O} + n\text{H}_2\text{O}$.

System. Orthorhombic (in certain conditions tetragonal). Also amorphous.

Habit. Prisms with vertical striations; scaly or tabular || (010).

Structure. Crystalline, massive.

Cleavage. Perfect || (010).

Fracture. Irregular.

Hardness. 5-5.5.

Spec. Grav. 4.0-4.4.

Lustre. Submetallic, dull.

Colour. Brown, yellow, red.

Mag. Prop. Moderately magnetic.

Elect. Prop. Moderate conductor.

Opt. Prop. R.I. very high, $\alpha = 2.15$, $\beta = 2.22$, $\gamma = 2.224$. Birefringence strong, $\gamma - \alpha = 0.074$. Optically biaxial, negative. Optic orientation varies for light of different wave length, optic axial plane being (100) for red light and (001) for yellow light etc. Uniaxial for light of wave-length 610-620 $\text{m}\mu$ (A. N. Winchell). $Bxa \perp (010)$; prisms have positive elongation. Pleochroism variable (seen in thin section): X = clear yellow, Y = brownish yellow, Z = orange yellow. Strong dispersion.

Characters in Sediments. Detrital goethite is probably far more common in sediments than records indicate. The tendency to diagnose "limonite" (p. 309) for most apparently amorphous brown grains common in many sandstones, for instance, would probably be checked on closer examination under high power. The essential difference between goethite and limonite is the crystal form and anisotropic character of the former, also its pleochroism seen in sufficiently thin, translucent grains. With dark ground illumination goethite grains appear grey and submetallic. Sometimes a fibrous tendency is observed which is possibly an intermediate stage in transformation to limonite.

Occurrence. Lower Carboniferous sandstone, West Cumberland.¹

Possible Sources of Derivation. Sedimentary iron ore deposits.

REMARKS.—In more massive iron ore deposits, much of the so-called "limonite" is in reality goethite.

Reference.

¹ H. P. Lewis, *Geol. Mag.*, 68, 1931, p. 554.

General Reference.

E. Posnjak and H. E. Merwin, *Amer. Journ. Sci.*, 47, 1919, p. 311.

GRAPHITE

Chem. Comp. Carbon, sometimes with iron and silica.

System. Trigonal.

Habit. Tabular (six-sided) plates or lamellæ, often rounded; sometimes striated || trace of unit rhombohedron (10 $\bar{1}$ 1).

Structure. Crystalline, columnar, radiate, granular, compact, earthy.

Cleavage. Perfect || (0001); indistinct || (10 $\bar{1}$ 1).

Fracture. Irregular.

Hardness. 1-2.

Spec. Grav. 2.25.

Lustre. Metallic, sometimes dull, "soot-black."

Colour. Steel-grey to "soot-black." Opaque.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. very high, $n=2.0\pm$. Normally opaque. In extremely thin flakes, translucent and transmits greenish light; such flakes are uniaxial negative.

Characters in Sediments. Occurs in the form of rounded, platy or irregular dull black grains, recognised chiefly by their appearance in reflected light.

Occurrence. In Devonian limestones of the Torquay district ("Carbon");¹ shore sands of the coast of North Cornwall;² beach sands of Florida, U.S.A.^{3, 4}

Possible Sources of Derivation. Metamorphic rocks: gneisses, phyllites, schists, altered limestones, quartzites.

REMARKS.—Detrital graphite is essentially a local species, hardly to be expected in ordinary sediments unless graphite-rich rocks have been laid under contribution to them. Certain shore sands lying close to phyllites which have undergone disintegration yield both free and composite grains of graphite, in the latter case associated generally with quartz.

References.

¹ W. G. Shannon, *Proc. Geol. Assoc.*, 39, 1928, p. 150.

² Author's observations. See also P. G. H. Boswell, *Proc. Liverpool Geol. Soc.*, 13, 1923, p. 268.

³ J. H. C. Martens, 19th *Ann. Rep. Florida Geol. Surv.*, 1928, p. 154.

⁴ J. H. C. Martens, *Bull. Geol. Soc. Amer.*, 46, 1935, p. 1580.

GROSSULARITE

(GARNET GROUP)

Chem. Comp. $3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{SiO}_2$.

System. Isometric.

Habit. Dodecahedral (110); trapezohedral (211) often modified by hexoctahedral faces. Striations often || (110).

Structure. Crystalline.

Cleavage. None.

Fracture. Irregular.

Hardness. 6.

Spec. Grav. 3.4-3.6.

Lustre. Vitreous.

Colour. Yellow, brown, green, colourless. Transparent to translucent

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. high, $n=1.735$. Optically isotropic. Often optically anomalous due to strain (? twinning), when crystals exhibit weak birefringence, biaxial negative characters and large optic axial angle. Such examples show strong dispersion but are non-pleochroic.

Characters in Sediments. Yellow-brown detrital grossularite is not a rare constituent of sediments derived from favourable contact-altered rocks such as metamorphosed limestones and schists. Dodecahedral or more complex forms are found as rounded or subangular grains having characteristic "garnet" features. Alteration to epi-

dote, chlorite minerals and calcite may be noted. High relief, colour, form, fracture, absence of cleavage and normally isotropism unite to distinguish this species.

Occurrence. In Triassic gypseous deposits and dolomites near Jena, Germany;¹ in the limestone soils of the East Indian Archipelago;² in river concentrates, Belgian Congo.³

Possible Sources of Derivation. Metamorphosed limestone; schist; nepheline-syenites.

References.

- ¹ E. Kalkowsky, *Zeitschr. deutsch. geol. Gesellsch.*, 73, 1922, p. 1.
- ² J. Van Baren, *Comm. Geol. Inst. Agric. Univ. Wageningen*, 14, 1928.
- ³ H. Buttgenbach, *Ann. Soc. géol. Belg. Liège*, 46, 1923, p. B. 229.

GYPSUM (Selenite)*

[Pl. 20 A, B, facing p. 297.]

Chem. Comp. $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$.

System. Monoclinic.

Habit. Simple, tabular || (010) or prismatic, elongated or acicular || vertical axis c. Frequently twinned on (100), less commonly on (101).

Structure. Crystalline, fibrous, massive or granular.

Cleavage. Perfect || (010), imperfect || (100) and ($\bar{1}11$).

Fracture. None. Glide planes may be developed || (103) and (509).

Hardness. 1.5-2.

Spec. Grav. 2.32.

Lustre. Vitreous to dull; pearly on (010) faces.

Colour. Colourless, white, sometimes stained by impurity. Transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low, $\alpha = 1.520$, $\beta = 1.523$, $\gamma = 1.530$. Birefringence moderate, $\gamma - \alpha = 0.010$. Optically biaxial, positive. Optic axial plane || (010). $Bxa = Z$ inclined at $37\frac{1}{2}^\circ$ to normal of (100) and makes the complementary angle of $52\frac{1}{2}^\circ$ with the c axis in the obtuse angle β . $Y || b$. Fibres fast || length. Optic axial angle large, $2E = 95^\circ$, $2V = 58^\circ$. (010) folia give extinction angles of 13° and 37° . Strong inclined dispersion, $\rho > v$. Optical properties vary considerably with temperature.

Characters in Sediments. Found as colourless, well formed crystals (selenite), often somewhat rounded; or as "platy" cleavage fragments of a pseudo-rhombohedral character and determined by (010) cleavage. Other developments noted include fibrous and matted types, spherulites and radiating clusters; these frequently show brush-polarisation; twinned crystals, about (100), also occur, the plane of composition being represented by a sharply defined line from which the two halves of the crystal extinguish at an angle of $37\frac{1}{2}^\circ$. Twinned and corroded selenites have been described from the London Clay and are good examples of these developments.⁶ The irregularly shaped grains and aggregates of gypsum (as distinct from the crystalline selenite) met with in sandstones etc., are probably derived from the disintegration of the mineral occurring in the form of a cementing medium; in this respect the grains resemble the haphazard forms of

* Selenite is the name used generally for crystalline varieties of the more common massive gypsum deposits.

barite (*q.v.* p. 248) from which, however, they are readily distinguished by optical properties. Immature developments from anhydrite (*q.v.* p. 239) are common in some rocks; such grains have a higher S.G. than normal gypsum, also a higher R.I. than Canada balsam, though the characteristic properties of anhydrite, *e.g.* cleavage, form, are usually obscured. In the crystalline forms (selenite), zoning is often a feature, the zones being picked out by iron-ore inclusions; of the latter, rutile, apatite, hematite, magnetite are among those most commonly noted. Diagonal striæ common. Selenite and gypsum are both diagnosed primarily by their low S.G., habit, colour and low R.I. (lower than Canada balsam), the crystalline variety, by very distinctive optical properties as noted above.

Occurrence. In the New Red Sandstone of the West of England;¹ massive gypsum in the Triassic deposits of the Midlands, notably Nottinghamshire² and Leicestershire;³ selenite in the Kimmeridge Clay, Shotover Hill, Oxford;⁴ also in the Upper Kimmeridgian of Buckinghamshire;⁵ in the London Clay of Thornton Heath, Surrey,⁶ and at Harefield, Middlesex.⁷ Many of the Miocene clays and marls of different countries yield beautiful varieties of selenite, *e.g.* the Naparima Marls, Trinidad, the Lower Fars of Iraq and Iran,⁸ the latter countries famous also for their vast developments of massive gypsum.

Possible Sources of Derivation. Sedimentary rocks, saline deposits, from volcanic regions and metalliferous veins.

REMARKS.—There is good reason to believe that crystalline gypsum (selenite) occurs far more commonly in argillaceous rocks in the British Isles than the scanty records available would suggest. In washing out the light materials of such sediments, much of this gypsum may be lost or otherwise overlooked. It is certainly an interesting species and, like anhydrite, repays study, especially for the many and varied forms exhibited.

References.

¹ H. H. Thomas, *Quart. Journ. Geol. Soc.*, 65, 1909, p. 231.

² W. H. Richardson, *Mineral Mag.*, 19, 1921, p. 196.

³ T. O. Bosworth, "Keuper Marls around Charnwood." *Leicester Lit. and Phil. Soc.*, 1913, ch. ix.

⁴ Well-known locality.

⁵ W. Neaverson, *Proc. Geol. Assoc.*, 36, 1925, p. 253.

⁶ G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915-16, p. 95.

^{7, 8} Author's observations.

HALLOYSITE

Chem. Comp. $\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$.

System. Isometric or amorphous.

Habit. White amorphous powder. Often colloidal.

Structure. Indefinite.

Cleavage. None.

Fracture. ?

Hardness. 2.

Spec. Grav. 2.6.

Lustre. Earthy.

Colour. White.

Mag. Prop. Non-magnetic.

Elect. Prop. ?

Opt. Prop. R.I. low, $n=1.47-1.57$ (increases on drying). Optically isotropic.

Characters in Sediments. Halloysite occurs in kaolinitic clays in which it has been identified in fine colloid fractions; also it occurs as beds and veins in certain ball clays etc. Generally takes the form of white shapeless particles which are insoluble in acid and is identified by its R.I. (lower than Canada balsam) and powdery appearance. It is probably much commoner in sedimentary rocks than existing records indicate.

Occurrence. In clays from various stratigraphical horizons in the Cambrian, Carboniferous and Upper Cretaceous, U.S.A.;¹ in clays of the Eastern United States;² in the Chalk, Worms Heath, Surrey.³

Possible Sources of Derivation. Ball clay, china clay, shale, Fuller's earth.

References.

¹ R. E. Somers, *Journ. Washington Acad. Sci.*, 9, 1919, p. 113.

² H. Ries, W. S. Bayley and Others, *U.S. Geol. Surv. Bull.* 708, 1922.

³ G. M. Davies, in W. Whitaker, *Quart. Journ. Geol. Soc.*, 75, 1920, p. 22.

General References.

C. S. Ross and P. F. Kerr, "Halloysite and Allophane." *U.S. Geol. Surv. Prof. Paper* 185—G, 1934.

R. E. Grim and R. H. Bray, "The Mineral Constitution of Various Ceramic Clays." *Journ. Amer. Ceram. Soc.*, 19, 1936, p. 307.

HEMATITE

Chem. Comp. Fe_2O_3 .

System. Trigonal.

Habit. Euhedral; tabular || (0001); platy.

Structure. Crystalline, laminated, massive or earthy.

Cleavage. Doubtful. Parting || (0001) and (1011), due to lamellar twinning.

Fracture. Subconchoidal, irregular.

Hardness. 5.

Spec. Grav. 5.2.

Lustre. Brilliant, metallic. Earthy varieties red.

Colour. Steel-grey. Translucent to opaque.

Mag. Prop. Moderately magnetic.

Elect. Prop. Good conductor.

Opt. Prop. Opaque in thick scales or grains. Translucent plates show very high R.I., $\omega=3.22$, $\epsilon=2.94$ and extreme birefringence, $\omega-\epsilon=0.28$; polarisation tint often masked by natural colour. Optically uniaxial, negative. Pleochroic in sections \perp basal plane: ω = brownish-red, ϵ = yellowish-red.

Characters in Sediments. Commonly found as irregular or rounded, earthy grains of a reddish-brown colour by reflected light, which is very characteristic. More rarely as rhombohedral grains or "platy" forms with splendid lustre. H. H. Thomas has described "minute botryoidal grains, made up of spheroidal masses with radiate structure which give a black cross between crossed nicols."³

Occurrence. In Devonian sediments of the Torquay district;¹ in Permian rocks of the Torquay Promontory;² in the New Red Sandstone of the West of England;³ in the Keuper Marls of Charnwood, Leicester-

shire;⁴ in the Fairlight Clay (Wealden) of Sussex;⁵ in the Thanet Beds, Reading Beds and London Clay of the N.E. part of the London Basin;⁶ in the dune sands of South Wales;⁷ in surface deposits of S.E. Devonshire;⁸ in Dartmoor detritals.⁹

Possible Sources of Derivation. Igneous and metamorphic rocks; metaliferous veins; limestones.

REMARKS.—Hematite occurs in sediments both as a primary and secondary constituent. In the latter case its partial alteration to limonite may frequently be observed. A common "cementing" medium in sandstones.

References.

- ¹ W. G. Shannon, *Proc. Geol. Assoc.*, 39, 1928, p. 140 etc.
- ² W. G. Shannon, *Proc. Geol. Assoc.*, 38, 1927, p. 134.
- ³ H. H. Thomas, *Quart. Journ. Geol. Soc.*, 65, 1909, p. 232.
- ⁴ T. O. Bosworth, "Keuper Marls around Charnwood," *Leicester Lit. and Phil. Soc.*, 1913, p. 94.
- ⁵ H. B. Milner, *Proc. Geol. Assoc.*, 36, 1925, p. 315.
- ⁶ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 71, 1915, table iv, p. 576, 578.
- ⁷ A. Stuart, *Proc. Geol. Assoc.*, 35, 1924, p. 320.
- ⁸ W. G. Shannon, *Geol. Mag.*, 64, 1927, p. 146, 148.
- ⁹ A. Brammall, *Proc. Geol. Assoc.*, 39, 1928, p. 35.

HERCYNITE

(SPINEL GROUP)

Chem. Comp. $\text{FeO} \cdot \text{Al}_2\text{O}_3$.

System. Isometric.

Habit. Octahedral, more commonly granular.

Structure. Fine granular, massive.

Cleavage. Imperfect || (111).

Fracture. Uneven.

Hardness. 7.5.

Spec. Grav. 3.9.

Lustre. Vitreous, dull.

Colour. Black, blackish green. Translucent to opaque.

Mag. Prop. Weakly magnetic.

Elect. Prop. Weak conductor.

Opt. Prop. R.I. very high, $n = 1.80 \pm$. Optically isotropic.

Characters in Sediments. On account of its dark colour hercynite is probably often overlooked in detrital sediments of relevant provenance.

If grains are thin (at edges) a characteristic grass-green colour is noted. Otherwise as isolated grains, this species presents difficulties in positive diagnosis by microscopical means alone.

Occurrence. In the zirconiferous sandstone near Ashland, Virginia, U.S.A.¹

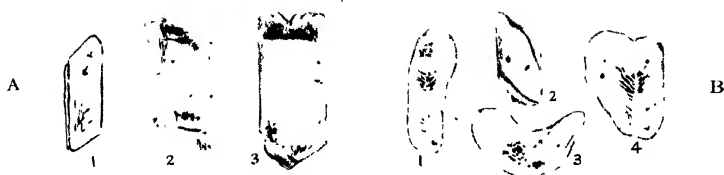
Possible Sources of Derivation. Contact-altered rocks rich in alumina.

Reference.

- ¹ T. L. Watson and F. L. Hess, *U.S. Geol. Surv., Bull.* 530, 1913, p. 165.

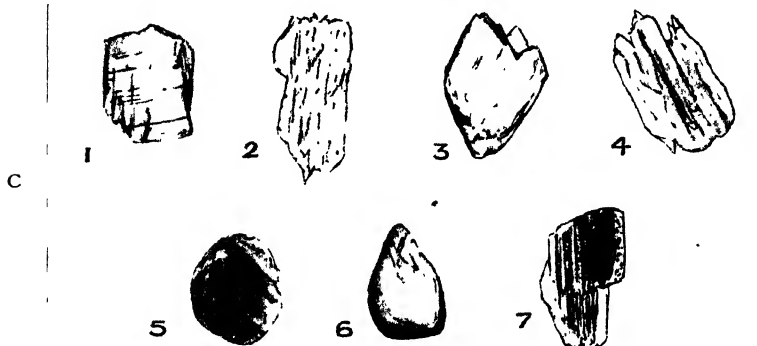
HIDDENITE

(VARIETY OF SPODUMENE, *q.v.* p. 340.)



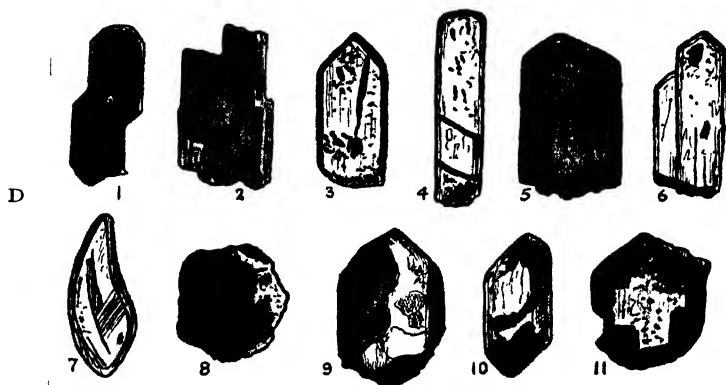
A, B. GYPSUM.

- A 1-3 Recent Sand, Bulawayo, Rhodesia [x 30]
 B 1-4 London Clay, Thornton Heath, Surrey [x 40]
 N.B. B 1, 3 and 4 are twinned on (100). (From brush-drawings by F. Smithson)



C GLAUCOPHANE AND HORNBLÉNDE.

- C 1, 3 Glaucophane from Miocene Sands, Trinidad [x 70]
 C 2, 4 Hornblende from Miocene Sands, Trinidad [x 70]
 C 5 Glaucophane from Blown Sands, Newgale, Pembrokeshire [x 70]
 C 6 Glaucophane from Glacial Sands, Withybush, Haverfordwest, Pembrokeshire [x 40]
 C 7 Hornblende from Blown Sands, Newgale, Pembrokeshire [x 40]



D. HYPERSTHENE.

- D. 1-3. Sand from Fiji Is. [x 25]
 D. 4-6. Volcanic Sand, Mont Pelée, Martinique [x 25]
 D. 7. Shore Sand, S. E. Arabia. [x 25]
 D. 8. Recent Sand, Gold Coast, W. Africa [x 25]
 D. 9-12. Pleistocene Sand, Portugal. [x 25]

HORNBLLENDE [Pl. 20 c, facing p. 297.]

(AMPHIBOLE GROUP)

Chem. Comp. $\text{Ca}_2\text{Na}_2(\text{Mg}, \text{Fe})_6(\text{Al}, \text{Fe})_4\text{Si}_{14}\text{O}_{44}(\text{OH})_4$.**System.** Monoclinic.**Habit.** Prismatic, elongated $\parallel c$.**Structure.** Crystalline, tending to fibrous (actinolite, p. 229), massive.**Cleavage.** Perfect $\parallel (110)$; less distinct $\parallel (100)$ and (010) . Cleavage traces in cross sections (\perp prism zone) intersect at angle of $124^\circ 11'$. Parting observed in twin crystals $\parallel (100)$, (010) and (001) .**Fracture.** Uneven, subconchoidal. Frequently occurs at right angles to prismatic cleavage.**Hardness.** 5-6.**Spec. Grav.** 3.3, varying with composition.**Lustre.** Vitreous.**Colour.** Dark green, brown, black. Translucent.**Mag. Prop.** Moderately magnetic.**Elect. Prop.** Moderate conductor.**Opt. Prop.** R.I. high, $\alpha = 1.654$, $\beta = 1.666$, $\gamma = 1.670$. Birefringence moderate, $\gamma - \alpha = 0.016$. Optically biaxial, negative. Optic axial plane $\parallel (010)$. $Bxa = X$ inclined at low angle to normal of (100) . Length and cleavage trace slow (positive). Oblique extinction. $Z \wedge c$ in (010) in obtuse angle β varies from $15^\circ - 25^\circ$. $Y \parallel b$. Pleochroism varies, maximum absorption being in direction $\parallel Z$: $X = \text{yellow}$ or pale green $< Y = \text{straw-yellow}$ or yellow-green $< Z = \text{brown}$ or dark green. Dispersion, $\rho < \nu$.**Characters in Sediments.** Green hornblende is most characteristic of detrital sediments, the brown type being rare (p. 508). Grains are usually in the form of elongated "platy" cleavage flakes determined by (110) and with frayed ends. (010) grains or cleavage flakes also noted. Prismatic striae are a feature of certain types. The colour may be unevenly distributed in the grain, being densest in the middle and becoming gradually paler towards the boundaries, especially the terminations, where the pleochroism is often best observed. Pleochroism is variable; some grains are non-pleochroic; most show weak colour-change, a few exhibiting strong properties in this respect, especially the soda-bearing types. The common pleochroism noted is the change from the pale colour (in the N.-S. position) to darker shades in the E.-W. position (the latter vibrations parallel to the short axis of the polariser). Inclusions of magnetite, rutile, apatite and titanite have been observed in common hornblende, but they are not particularly frequent. Alteration is mainly to chloritic matter and all stages of decomposition are detectable in detrital grains. Diagnosed chiefly by form, colour, marked prismatic cleavage, weak pleochroism and characteristic extinction angle.**Occurrence.** In Devonian sediments of the Torquay district;¹ in the Sandringham Sands, Snettisham Clay and Carstone (Lower Greensand) of Norfolk;² greenish-blue type in the Carstone of Hunstanton, Norfolk;³ in the Red Chalk of Hunstanton;⁴ in the Eocene and Oligocene deposits of the Haldon Hills and Bovey Tracey, Devonshire, respectively;⁵ in the Thanet Beds and London Clay of the N.E. part of the London Basin;⁶ in the Bagshot Beds of Essex⁷ and of N.W. London;⁸ in the Pliocene sands of Bentley, Suffolk and Walton-on-Naze, Essex;⁹ in the later Tertiary deposits of the East of England;¹⁰ in the dune sands of South Wales (including barkevite);¹¹ in glacial sands etc., of the Dublin district;¹² in shore

sands of Guernsey;¹³ in blown sands from Newgale, Pembroke-shire.¹⁴

Possible Sources of Derivation. Igneous and metamorphic rocks, especially granite, syenite, diorite and equivalent volcanic types and also hornblende schist etc.

Note.—The closely allied members of the amphibole group are now described separately, as follows:—

Actinolite, p. 229.
 Arfvedsonite, p. 246.
 Barkevicite, p. 250.
 Basaltine, p. 250.
 Gastaldite, p. 290.
 Glaucothane, p. 289.
 Riebeckite, p. 333.
 Tremolite, p. 349.

References.

- ¹ W. G. Shannon, *Proc. Geol. Assoc.*, 39, 1928, p. 137.
- ² H. C. Versey and C. Carter, *Proc. Yorks. Geol. Soc.*, 20, 1926, p. 350.
- ³ R. H. Rastall, *Geol. Mag.*, 1919, p. 214.
- ⁴ H. C. Versey and C. Carter, *op. cit.*, p. 360.
- ⁵ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 79, 1923, p. 226.
- ⁶ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 71, 1915, p. 577, 580.
- ⁷ S. W. Wooldridge, *Proc. Geol. Assoc.*, 35, 1924, p. 377.
- ^{8, 9} Author's observations.
- ¹⁰ I. S. Double, *Proc. Geol. Assoc.*, 35, 1924, p. 341.
- ¹¹ A. Stuart, *Proc. Geol. Assoc.*, 35, 1924, p. 324.
- ¹² F. Smithson, *Geol. Mag.*, 65, 1928, p. 24.
- ^{13, 14} Author's observations.

HUMITE

(HUMITE GROUP)

Chem. Comp. $6\text{MgO} \cdot 3\text{SiO}_2 \cdot \text{Mg}(\text{F}, \text{OH})_2$.

System. Orthorhombic.

Habit. Small, tabular (100) or (001).

Structure. Crystalline.

Cleavage. Perfect || (001).

Fracture. Uneven.

Hardness. 6.

Spec. Grav. 3.1-3.3.

Lustre. Vitreous.

Colour. Colourless, white, yellow, brown. Transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. high, $\alpha = 1.622$, $\beta = 1.632$, $\gamma = 1.652$. Birefringence strong, $\gamma - \alpha = 0.030$. Optically biaxial, positive. Optic axial plane $\perp (010)$. $Bxa = Z \perp (010)$. Straight extinction || cleavage trace in (010) sections. $X = a$. $Z = b$. $2V = 67^\circ - 70^\circ$. $2E = 132^\circ$. Dispersion weak, $\rho > v$. Pleochroism weak: $X =$ golden yellow $> Z =$ pale yellow, colourless $> Y =$ pale yellow or colourless.

Characters in Sediments. A comparatively rare mineral in sediments which should, however, be searched for where contact-altered dolomites have been laid under contribution. Occurs in tabular, golden

yellow grains reminiscent of staurolite with which, doubtless, humite is often confused. It is to be noted that the golden yellow colour is \parallel X in humite and to Z in staurolite and this serves as a primary distinguishing feature. In colourless grains, humite may be confused with olivine (p. 319). The latter has a higher R.I., optic axial plane \parallel (001) (perfect cleavage in humite, not in olivine) and not \perp (001) as in humite; olivine is seldom, if ever, pleochroic, but even colourless humite is likely to exhibit faint pleochroism.

Occurrence. In the sands from the outlets of subterranean rivers at Cerno and Zmiriac, in the bay of Buscari.¹

Possible Sources of Derivation. Contact-altered dolomitic limestone. Vein mineral.

REMARKS.—In doubtful cases, alleged humite should be tested for fluorine to distinguish from other magnesian silicates. Note chief allied species of this group (not as yet recorded in sediments):—

Forsterite, $2\text{MgO} \cdot \text{SiO}_2$ (Orthorhombic).

Chondrodite, $4\text{MgO} \cdot \text{Mg}(\text{F}, \text{OH})_2 \cdot 2\text{SiO}_2$ (Monoclinic).

Clinohumite, $8\text{MgO} \cdot \text{Mg}(\text{F}, \text{OH})_2 \cdot 4\text{SiO}_2$ (Monoclinic).

Reference.

¹ M. Kispatic, *Verh. k.-k. Geol. Reichsanst.*, 1910, p. 294.

HYALITE

See Opal, p. 320.

HYPERSTHENE*

(PYROXENE GROUP) [Pl. 20 D, facing p. 297.]

Chem. Comp. $(\text{Mg}, \text{Fe})\text{O} \cdot \text{SiO}_2$.

System. Orthorhombic.

Habit. Prismatic, bipyramidal, tabular \parallel (100) or (010).

Structure. Crystalline, lamellar, granular, massive.

Cleavage. Distinct \parallel (110), fair \parallel (100) and (010).

Fracture. Uneven.

Hardness. 5-6.

Spec. Grav. 3.3-3.5.

Lustre. Vitreous, pearly on cleavage faces, submetallic, bronze-like (bronzite) on (010).

Colour. Brownish-green, grey-green, olive, brown, yellow-brown. Translucent.

Mag. Prop. Weakly magnetic, varies with iron content.

Elect. Prop. Moderate conductor.

Opt. Prop. R.I. high, $\alpha = 1.692$, $\beta = 1.702$, $\gamma = 1.705$. Birefringence moderate, $\gamma - \alpha = 0.013$. Optically biaxial, negative. Optic axial

* For *Enstatite*, the less ferriferous variety of rhombic pyroxene, see p. 281.

plane \parallel (010). $X \parallel a$, $Y \parallel b$, $Z \parallel c$. Straight extinction. $Bxa = X \perp (100)$. Optic axial angle varies with amount of FeO present. $2V = 75^\circ$ (decreases with increase of Fe). Dispersion weak, $\rho > v$. Pleochroism marked in the more ferriferous varieties: $X = \text{pink}$ or red, $Y = \text{yellow}$, $Z = \text{green}$.

Characters in Sediments. Not a common mineral in sediments as a rule, but to be anticipated in deposits derived from contiguous hypersthene-bearing igneous rocks. It usually assumes a ragged, prismatic habit and displays characteristic pleochroism, pink, red or brown to green (as above). Grains often full of minute inclusions (Schiller-structure), identified as iron-ore or some form of TiO_2 . Detrital hypersthene is usually pale brownish-green to greyish-green in colour, though exceptionally deep brown euhedral varieties occur (with striking green pleochroism) in the vicinity of volcanic lavas. The (110) cleavage is often conspicuous.

Occurrence. In the Silurian Rocks of Southern Scotland;¹ "Apart from Scottish occurrences, occasional pleochroic grains have been recorded from the Carboniferous of North Wales, the Permian of Lancashire, the Trias of the Vale of Clwyd, the Middle Lias, Portlandian, Lower Greensand, Headon Beds and London Clay";² in the Lower Permian rocks at Skillan Clough and Bentley Brook, Ormskirk;³ in the Northampton Ironstone (Inferior Oolite);⁴ in the Upper Kimmeridge Clay and Portland Sand of Thame etc., Buckinghamshire;⁵ in the Spilsby Sandstone (Lower Cretaceous);⁶ in the Boulder Clay of Dimlington, Yorkshire;⁷ in the dune sands of South Wales;⁸ deep brown prisms in superficial deposits, Mont Pelee, Martinique;⁹ in the shore sand, Kynance Cove, Cornwall;¹⁰ in the sands of the Northumberland Coast;¹¹ in the sands of Red Wharf Bay, Anglesey;¹² in the Clyde Alluvium, Scotland.¹³

Possible Sources of Derivation. Intermediate, basic and ultrabasic igneous rocks, e.g. gabbro (norite), dolerite, basalt and volcanic rocks generally.

REMARKS.—If hypersthene is anticipated in a sample, avoid using strong HCl in cleaning; some varieties are readily attacked by acid, enstatite being more stable in this respect. The variety "bronzite" is characterised by distinctive lustre and "schiller" inclusions: see also under *enstatite*, p. 281.

References.

- ¹ W. Mackie, *Rep. Brit. Assoc.*, 1928 (Glasgow), 1929, p. 556.
- ² P. G. H. Boswell, *Trans. Geol. Soc. Glasgow*, 18, 1926-27, p. 140.
- ³ M. Workman, *Proc. Liverpool Geol. Soc.*, 13, 1923, p. 308.
- ⁴ J. G. A. Skerl, *Proc. Geol. Assoc.*, 38, 1927, p. 381.
- ⁵ E. Neaverson, *Proc. Geol. Assoc.*, 36, 1925, p. 250.
- ⁶ F. T. Ingham, *Proc. Geol. Assoc.*, 40, 1929, p. 1.
- ⁷ A. Raistrick, *Geol. Mag.*, 66, 1929, p. 337.
- ⁸ A. Stuart, *Proc. Geol. Assoc.*, 35, 1924, p. 324.
- ^{9, 10} Author's observations.
- ¹¹ L. Hawkes and J. A. Smythe, *Geol. Mag.*, 68, 1931, p. 345.
- ¹² P. G. H. Boswell, *Proc. Liverpool Geol. Soc.*, 15, 1928, p. 60.
- ¹³ B. H. Barrett, *Trans. Geol. Soc. Glasgow*, 17, 1926, p. 402.

General Reference.

- N. F. M. Henry, "Some data on the Iron-Rich Hypersthene." *Mineral. Mag.*, 24, 1935, p. 221.

IDDINGSITE

Chem. Comp. $\text{MgO} \cdot \text{Fe}_2\text{O}_3 \cdot 3\text{SiO}_2 \cdot 4\text{H}_2\text{O}$.

System. Orthorhombic.

Habit. Pseudomorphous (usually after olivine). Lamellar.

Structure. Crystalline, aggregated.

Cleavage. Perfect $\parallel (100)$, (001) , (010) ; fair $\parallel (101)$.

Fracture. Uneven.

Hardness. 3.

Spec. Grav. 2.5-2.84.

Lustre. Vitreous.

Colour. Red, reddish-brown, translucent.

Mag. Prop. Moderately magnetic.

Elect. Prop. Weak conductor.

Opt. Prop. Variable with composition. R.I. high, $\alpha = 1.674$, $\beta = 1.715$, $\gamma = 1.718$. Birefringence strong, $\gamma - \alpha = 0.044$. Optically biaxial, negative (also more rarely positive). Optic axial plane $\parallel (010)$. $X = a$. $Y = b$. $2V = 35^\circ \pm$. $2E = 62^\circ$. Dispersion strong, $\rho > \nu$. Pleochroism: $X < Y < Z$ (in red-brown grains).

Characters in Sediments. Irregular grains of red or reddish brown colour, characterised by cleavages (as above), high relief and distinctive pleochroism.

Occurrence. In certain soils of the U.S.A.;^{1, 2} in sea-bed deposits in the area between Corsica, Sardinia and Sicily.³

Possible Sources of Derivation. Olivine (in basic igneous rocks).

References.

¹ G. N. Coffey, *U.S. Bur. Soils, Bull.* 85, 1912.

² W. H. Fry, *Econ. Geol.*, 10, 1915, p. 292.

³ F. Salmoiraghi, *Rend. R. Ist. lombardo*, 42, 1909, p. 719.

ILMENITE (Manaccanite)

Chem. Comp. $\text{FeO} \cdot \text{TiO}_2$.

System. Trigonal.

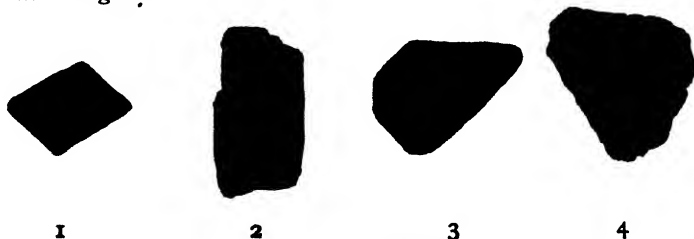


FIG. 81. Ilmenite.

1-3. Demerara, British Guiana. [$\times 60$.]

4. Alluvials, Ceylon. [$\times 20$.]

Habit. Rhombohedral $(10\bar{1}1)$ with prominent base (0001) ; lamellar. Twinning on (0001) and $(10\bar{1}1)$.

Structure. Crystalline or in compact platy masses.

Cleavage. None. Parting sometimes developed $\parallel (0001)$ and in twin crystals.

Fracture. Conchoidal.

Hardness. 5-6.

Spec. Grav. 4.5-5.

Lustre. Submetallic, steel-grey, often with crimson or purplish sheen.

Colour. Iron-black.

Mag. Prop. Moderately magnetic.

Elect. Prop. Good conductor.

Opt. Prop. Opaque, purplish-brown in very thin section, when it is translucent (edges of grain), exhibiting a high R.I. and very strong birefringence.

Characters in Sediments. Commonly occurring in irregular, subangular grains, with characteristic purple-grey or sometimes crimson sub-metallic lustre in reflected light. Grains quite opaque in transmitted light. Partial alteration to leucoxene (p. 308) observed sometimes.

Occurrence. An ubiquitous species in detrital sediments; far commoner than any other iron-ore, including magnetite. Recorded from deposits of every stratigraphical horizon: Pre-Cambrian to Recent. For alluvial types see C. Raeburn and H. B. Milner, "Alluvial Prospecting," (Murby, London), 1927, p. 398.

Possible Sources of Derivation. Igneous rocks, especially basic and ultra-basic types.

REMARKS.—Ilmenite frequently presents characters which render discrimination between it and associated magnetite a matter of great difficulty under the microscope. Strong dark ground illumination may aid its identification and an initial concentration can also be effected by extracting the magnetite with a powerful horseshoe or bar magnet. Where partial alteration to leucoxene occurs, there may be little fear of confusion, but it is to be noted that titaniferous magnetite may show much the same characteristics and tendencies.

JASPER

(VARIETY OF CHALCEDONY, *q.v.* p. 261)

KAOLINITE

Chem. Comp. $\text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$.

System. Monoclinic.

Habit. Flattened $\parallel (001)$; pseudo-hexagonal or rhombohedral plates, often curved.

Structure. Commonly amorphous, powdery or in laminated aggregates; more rarely crystalline.

Cleavage. Perfect basal $\parallel (001)$.

Fracture. Irregular.

Hardness. 2-2.5.

Spec. Grav. 2.6-2.63.

Lustre. Pearly on (001), otherwise dull or earthy.

Colour. White, yellow or brown. Translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low, $\alpha = 1.561$, $\beta = 1.565$, $\gamma = 1.566$. Birefringence weak, $\gamma - \alpha = 0.005$. Optically biaxial, negative. Optic axial plane $\perp (010)$.

$Bxo = Z \perp (010)$. $Bxa = X$ inclined at 4° to c. $Z \parallel b$. Y nearly $\parallel a$. $2V = 10^\circ - 57^\circ$. Dispersion weak, $\rho > v$. Coloured crystals pleochroic, $X =$ colourless, $Y = Z =$ cream-buff, or $X =$ cream-buff, $Y = Z =$ dark olive, buff (A. N. Winchell).

Characters in Sediments. Occurs commonly as irregular, colourless aggregates, wisps or as pseudo-rhombohedral scaly masses, characteristic of the light material of the sediment. Very perfect euhedra are sometimes obtainable from certain clays: see Fig. 82.

Occurrence. In clays related to "bentonite," U.S.A.;¹ in Pliocene silts of St. Agnes, Cornwall;² in the recent volcanic soil of Java.³

Possible Sources of Derivation. Altered acid igneous and aluminous rocks. Common alteration product of felspar; clays.

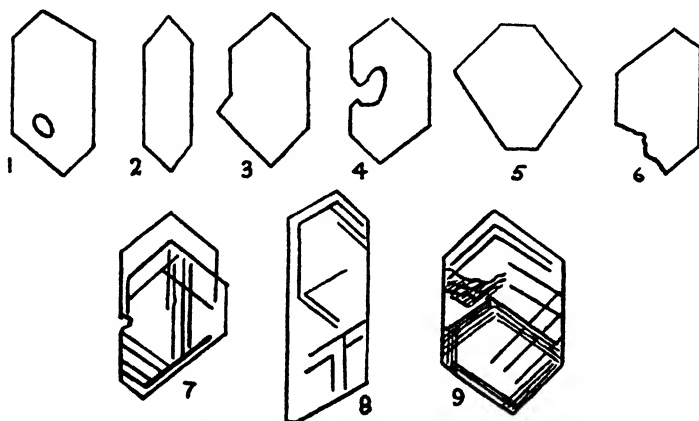


FIG. 82. Kaolinite from Clay. 1—6, Denver, Colorado, 7—9, Amlwch.

REMARKS.—Kaolinite may be confused with muscovite, from which it may be distinguished by its lower R.I., birefringence and by absence of good interference figure (characteristic of mica) in (001) cleavage flakes. It is a mineral easily overlooked. *Anauxite* ($Al_2O_3 \cdot 3SiO_2 \cdot 2H_2O$) is a clay mineral isomorphous with kaolinite.

References.

- ¹ C. S. Ross and E. V. Shannon, *Journ. Amer. Ceramic Soc.*, 9, 1926, p. 77.
- ² H. B. Milner, *Quart. Journ. Geol. Soc.*, 78, 1922, p. 357.
- ³ D. A. Carroll, *Journ. Roy. Soc. West Australia*, 20, 1933-4, p. 100.

General Reference.

- C. S. Ross and P. F. Kerr, "The Kaolin Minerals." *Geol. Mag.*, 69, 1932, p. 188.

KUNZITE

(VARIETY OF SPODUMENE, q.v. p. 340)

KYANITE.

[Pl. 5, facing p. 172, and Pl. 21 A, facing p. 309.]

Chem. Comp. $\text{Al}_2\text{O}_3 \cdot \text{SiO}_2$.**System.** Triclinic.**Habit.** Elongated prismatic ("bladed") crystals || c with irregular terminations. Fibrous. Distorted crystals not uncommon. Lamellar twinning about (100).**Cleavage.** Perfect || (100), fair || (010), trace || (001). Parting planes || (001) and (308) in twin crystals.**Fracture.** Ragged.**Hardness.** Varies from 4-7 with direction: 4-5 on (100) || length of crystal, 7 on (010).**Spec. Grav.** 3.6-3.68, being higher in coloured varieties.**Lustre.** Vitreous, pearly.**Colour.** Colourless, white, greyish-green, blue. Transparent.**Mag. Prop.** Non-magnetic.**Elect. Prop.** Non-conductor.**Opt. Prop.** R.I. high, $\alpha = 1.712$, $\beta = 1.720$, $\gamma = 1.728$. Birefringence moderate, $\gamma - \alpha = 0.016$. Optically biaxial, negative. Optic axial plane inclined at 30° to prism-edge (100) (010). $Bxa = X$ almost \perp (100). Oblique extinction on (100), $Z \wedge c = 27^\circ - 32^\circ$; on (010) $Z \wedge c = 5^\circ - 8^\circ$; on (301) $X \wedge a = 0^\circ - 2.5^\circ$. $2V = 82^\circ - 84^\circ$. Pleochroism slight in deeply coloured varieties: X = colourless, Y = violet-blue, Z = dark cobalt blue. Dispersion slight, $\rho > \nu$.**Characters in Sediments.** Varies greatly in physical characters, the commonest type being the subangular prismatic grain (100), elongated in the direction of the principal axis, irregularly terminated and with or without traces of the (001) cleavage (? parting) at right angles to the length of the grain and (010) cleavage parallel to the prism-margins. A more abraded form is the short "stumpy" grain, usually well rounded and sometimes exhibiting re-entrants due to fracture of the prism face or to solution. Compound cleavage fragments, due to differential abrasion of (100) and (010) are often observed, re-entrants in such cases being very marked; these fragments are usually sharply angular. Grains flattened || (010) are rare: they give straight extinction and do not show the interference figure typical of the (100) grains. Pleochroic grains are extremely rare. Inclusions of carbonaceous matter common. In some of the older sedimentary deposits "shimmer-aggregates" are found; these consist of colourless cores of kyanite surrounded by cryptocrystalline micaceous material containing abundant inclusions. Such aggregates are for the most part decomposition products of kyanite and allied aluminous silicates. (H. H. Thomas, *Quart. Journ. Geol. Soc.*, 58, 1902, p. 627.)**Occurrence.** Numerous records in post-Armorian deposits. In Upper Lias-Inferior Oolite, West of England*;¹ in the Northampton Ironstone (refer specially for notes on decomposition);² in the Portland Sand of Dorset*;³ in the Ashdown Sand, Hastings, Sussex*;⁴ in the Carstone (Lower Greensand) of Yorkshire and Lincolnshire*;⁵ in the Lower Greensand of Norfolk, Bedfordshire etc.*;⁶ in the Thanet Sands, Reading Beds and London Clay of the N.E. London Basin*;⁷ in the Bagshot Beds of Essex*;⁸ in the Pliocene deposits of St. Erth and St. Agnes, Cornwall*;⁹ in the later Tertiary deposits of the East of England;¹⁰ in the dune sands of South Wales.¹¹ (N.B.—Occurrences denoted * are figured in the appropriate references below.)**Possible Sources of Derivation.** Metamorphic rocks, especially mica schist and certain gneisses.

REMARKS.—Owing to the variety of forms presented by this mineral in sediments, it is a valuable species for correlation purposes, since detailed study shows that certain types are characteristic of definite horizons. Kyanite frequently affords direct evidence of the source of origin of the material in which it occurs and by the degree of abrasion suffered it may signify the nature and potency of the transporting medium. It is found associated with garnet, staurolite, andalusite and corundum in many instances, both in metamorphic rocks and in relevant detrital sediments.

References.

- ¹ P. G. H. Boswell, *Geol. Mag.*, 61, 1924, p. 254.
- ² J. G. A. Skerl, *Proc. Geol. Assoc.*, 38, 1927, p. 384.
- ³ M. P. Latter, *Proc. Geol. Assoc.*, 37, 1926, p. 84.
- ⁴ H. B. Milner, *Proc. Geol. Assoc.*, 36, 1925, p. 315.
- ⁵ H. C. Versey and C. Carter, *Proc. Yorks. Geol. Soc.*, 20, 1926, p. 349.
- ⁶ R. H. Rastall, *Geol. Mag.*, 1919, p. 214, 271.
- ⁷ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 71, 1915, p. 577, 579 and *Pl.* 47.
- ⁸ S. W. Wooldridge, *Proc. Geol. Assoc.*, 35, 1924, p. 379.
- ⁹ H. B. Milner, *Quart. Journ. Geol. Soc.*, 78, 1922, p. 371.
- ¹⁰ I. S. Double, *Proc. Geol. Assoc.*, 35, 1924, p. 342.
- ¹¹ A. Stuart, *Proc. Geol. Assoc.*, 35, 1924, p. 325.

LABRADORITE

(PLAGIOCLASE FELSPAR GROUP)

Chem. Comp. Ab_2An_3 . $\text{Ab}_{50}\text{An}_{50}$ — $\text{Ab}_{30}\text{An}_{70}$ (A. N. Winchell).

System. Triclinic.

Habit. Tabular || (010). Polysynthetic twinning on (010) almost invariable. Other laws common (see albite, p. 231).

Structure. Crystalline, massive, granular.

Cleavage. Perfect || (001), (010), imperfect || (110).

Fracture. Irregular.

Hardness. 6.

Spec. Grav. 2.69 — 2.72.

Lustre. Vitreous, pearly.

Colour. Colourless, grey, green. Iridescence on (010).

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low, $\alpha = 1.559$, $\beta = 1.563$, $\gamma = 1.568$. Birefringence weak, $\gamma - \alpha = 0.009$. $Bxa = Z$ inclined at $55^\circ - 65^\circ$ to (010) and $30^\circ - 40^\circ$ to (001). $Bxo = X$ inclined at $15^\circ - 25^\circ$ to (001) and $8^\circ - 20^\circ$ to (010). $2V = 79^\circ$. $2E = 172^\circ$. Dispersion weak, $p > v$.

Characters in Sediments. Labradorite when found in sediments as individual grains is diagnosed by extinction angle measured from twin lamellæ ($30^\circ - 40^\circ$), by the "broadness" of these lamellæ and by the R.I. being greater than that of Canada balsam. Grains which do not exhibit such features are almost certain to be overlooked. Most detrital plagioclase feldspar is determined by cleavages, but labradorite does not seem to survive commonly in sediments. Inclusions of hematite and ilmenite are usual, other possibilities being pyroxenes and amphiboles. Prone to rapid alteration to sericitic mica, kaolinite or "saussurite," which may account for the comparatively scanty records of this species.

Occurrence. In the recent volcanic soil of Java;¹ in sands at Folly Beach, near Charleston, S. Carolina, U.S.A.²

Possible Sources of Derivation. Basic igneous rocks.

References.

¹ D. A. Carroll, *Journ. Roy. Soc. West Australia*, 20, 1933-4, p. 100.

² J. H. C. Martens, *Amer. Mineral.*, 16, 1931, p. 526.

LAWSONITE

Chem. Comp. $\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$.

System. Orthorhombic.

Habit. Prismatic, tabular. Twinned on (110).

Structure. Crystalline.

Cleavage. Perfect || (010) and (001); less perfect || (110).

Fracture. Uneven.

Hardness. 8.

Spec. Grav. 3.1.

Lustre. Vitreous, dull.

Colour. Colourless, blue.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. high, $\alpha = 1.665$, $\beta = 1.674$, $\gamma = 1.699$. Birefringence strong, $\gamma - \alpha = 0.034$. Optically biaxial, positive. Optic axial plane || (010). $Z = c$, $X = a$. Straight extinction || prism edge and (010) cleavage trace. $2V = 84^\circ$. Dispersion strong, $\rho > v$. Pleochroic in thick sections; $X = \text{blue}$, $Y = \text{yellow}$, $Z = \text{colourless}$.

Characters in Sediments. Usually a secondary mineral, often after lime-soda feldspar in basic rocks. Occurs as colourless or slightly blue prismatic or irregular grains characterised by high relief and cleavage. Liable to confusion with zoisite, but has stronger birefringence than that species; also with cordierite; the latter has more pronounced pleochroism, lower R.I. and is negative.

Occurrence. In the Miocene rocks of Central Italy;¹ at the base of the San Onofre Breccia, California (Lower Miocene);² in the Tiburn Peninsula, Marin Co., California and in the Pleistocene-Recent deposits of the Lazard area, San Joaquin Valley, California.³

Possible Sources of Derivation. Metamorphic rocks, schists; saussuritised gabbro.

References.

¹ I. Chelussi, *Atti Soc. Lig. Sci. nat.*, 21, 1910, p. 105.

² A. O. Woodford, *Univ. California Publ., Bull. Dept. Geol. Sci.*, 21, 1925, p. 159.

³ R. D. Reed and J. B. Bailey, *Bull. Amer. Assoc., Petrol. Geol.*, 11, 1927, p. 363.

LEPIDOLITE

(MICA GROUP)

Chem. Comp. $2\text{H}_2\text{O} \cdot \text{K}_2\text{O} \cdot \text{Li}_2\text{O} \cdot 2\text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2$ (A. F. Hallimond).

System. Monoclinic, ? Triclinic.

Habit. Tabular || (001) with pseudo-hexagonal or irregular outline; sometimes elongated. Twinning about plane \perp (001) common; contact plane (001).

Structure. Crystalline, laminated.

Cleavage. Perfect \parallel (001). Parting \parallel (010) and $\bar{1}11$. Parting and gliding planes \parallel various crystal faces produced by percussion.

Fracture. Irregular but rarely seen.

Hardness. 2.5-4.

Spec. Grav. 2.8-2.9.

Lustre. Vitreous to pearly.

Colour. Lilac to mauve, white, yellow, grey, pink. Transparent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low, $\alpha = 1.532$, $\beta = 1.555$, $\gamma = 1.555$. Birefringence moderate, $\gamma - \alpha = 0.023$. Optically biaxial, negative. Optic axial plane \perp (010). Bxa nearly \perp cleavage plane (001), hence most flakes yield good interference figure. $2E$ varies from $57^\circ - 84^\circ$; $2V = 0^\circ - 50^\circ$. Pseudo-uniaxial varieties also noted. Sometimes distinctly pleochroic: Y and Z = lilac or pink, X = colourless. Dispersion, $\rho > \nu$.

Characters in Sediments. Occurs much as muscovite does, in irregular cleavage flakes, but of characteristic lilac to mauve colour. The refractive index is higher than that of muscovite and the birefringence is also higher. Intimate association with muscovite (zonal structure) in the same flake may sometimes be noted. Inclusions are usually absent, a further point of distinction from white mica; where recorded they have been identified as rutile, zircon, cassiterite or topaz, usually with pleochroic haloes.

Occurrence. Hitherto unrecorded from British sediments. Mauve-coloured mica flakes are noted from time to time in sands, e.g. shore sands of East Anglia, which may be referable to this species. Not uncommon in some of the late Tertiary sands of the Los Angeles basin, S. California, U.S.A.¹

Possible Sources of Derivation. Granite, pegmatite. Pneumatolytic ore-bodies, e.g. topaz, cassiterite etc.

REMARKS.—Lepidolite is to some extent attacked by hydrochloric acid, so that flakes may show etching or apparent alteration due to the initial cleaning of the sediment. Muscovite is not thus affected.

Reference.

¹ Author's observations.

LEPIDOMELANE

(MICA GROUP)

Chem. Comp. Biotite rich in ferric iron; also containing TiO_2 .

System. Monoclinic.

Habit. Tabular, scaly. Pseudo-hexagonal six-sided prisms. Twinned on (110) in thin (001) laminæ.

Structure. Crystalline, massive, lamellar.

Cleavage. Perfect \parallel (001). Parting \parallel (010) and $\bar{1}11$

Fracture. Uneven.

Hardness. 3.

Spec. Grav. $3.1 \pm$.

Lustre. Vitreous, resinous, pearly.

Colour. Black, dark brown. Translucent to opaque.

Mag. Prop. Moderately magnetic.

Elect. Prop. Moderate conductor.

Opt. Prop. R.I. high, $\alpha = 1.615$, $\beta = 1.726$, $\gamma = 1.733$. Birefringence very strong, $\gamma - \alpha = 0.118$. Optically biaxial, negative (sometimes uniaxial, negative with $\omega = 1.64$, birefringence 0.05). Optic axial plane $\parallel (010)$. $Bxa = X \perp (001)$. $X \wedge c = \text{small}$. $Y = b$. $2V = 31^\circ$. $2E = 52^\circ$. Dispersion strong, $\rho < \nu$. Pleochroism weak: $Z = \text{dark brown to opaque}$, $Y = \text{dark brown to opaque}$, $X = \text{light brownish-yellow}$.

Characters in Sediments. As biotite, but distinguished by its dark colour, rich blackish-brown pearly lustre by reflected light, high R.I. and strong birefringence. Most flakes are basal and when thin enough yield discernible negative interference figures. Optical properties of lepidomelane vary with iron content.

Occurrence. Listed by P. G. H. Boswell.¹

Possible Sources of Derivation. Intermediate plutonic rocks, e.g. syenite, metamorphic rocks.

Reference.

¹ "On the Mineralogy of Sedimentary Rocks." (Murby, London), 1933, p. 6.

LEUCOXENE [Pl. 21 B, facing p. 309.]

Chem. Comp. A decomposition product of ilmenite, as yet ill-defined. It is probably for the most part a form of titanium dioxide (rutile or anatase); titanite has also been suspected, with possibly some carbonate. It has been described by J. P. Iddings as a form of anatase or perovskite.

System. Non-crystalline.

Habit. Irregular aggregates or as pseudomorphs after ilmenite.

Structure. Amorphous.

Spec. Grav. Varies from 3.5-4.5.

Lustre. Dull.

Colour. White, yellow or brown. Translucent to opaque.

Mag. Prop. Non-magnetic.

Elect. Prop. Moderate conductor.

Opt. Prop. High R.I. and birefringence, seen in translucent flakes.

Characters in Sediments. Commonly occurs as rounded grains, opaque in transmitted light, white or yellowish-white in reflected light, having an "unglazed porcelain" appearance. Sometimes a core of unaltered ilmenite may be observed, in which case the grain will appear weakly magnetic. A rough "pitted" surface is characteristic of most grains, best seen by reflected light. Where the mineral is reasonably translucent, aggregate polarisation may be observed with crossed nicols.

Occurrence. Ubiquitous in detrital sediments as with ilmenite (p. 301).

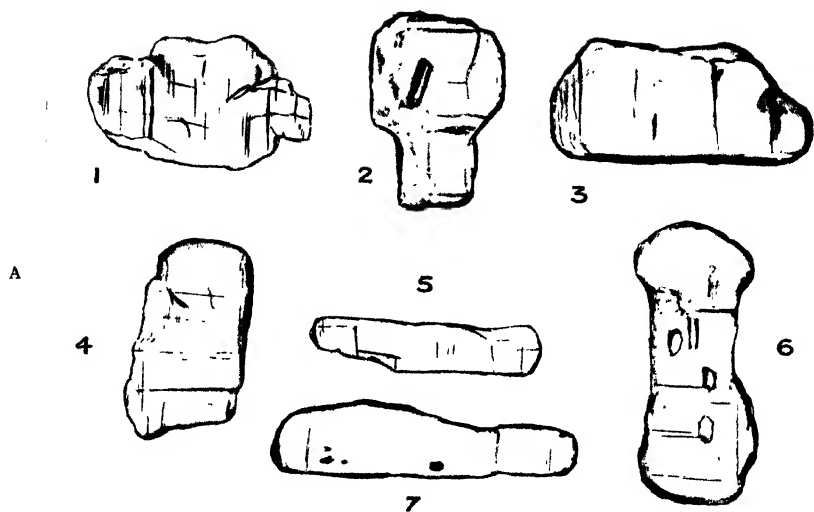
Possible Sources of Derivation. Essentially from ilmenite and largely *in situ*.

General References.

L. S. Brown, "The Occurrence of Leucoxene in some of the Permian Mid-Continent Sediments." *Amer. Min.* 13, 1928, p. 233.

F. Coil, "Chemical Composition of Leucoxene in the Permian of Oklahoma." *Amer. Min.*, 18, 1933, p. 62.

S. A. Tyler and R. W. Marsden, "The Nature of Leucoxene." *Journ. Sed. Pet.*, 3, 1938, p. 55.



A. KYANITE.

- A 1, 7 Lower Greensand, N.W. Wiltshire [x 60.]
 A 2, 3 Alluvials, West Africa [x 60.]
 A 4, 6 Bagshot Sands, Hampstead Heath, London [x 60.]
 A 5 Phreatic Sands, St. Agnes, Cornwall [x 60.]

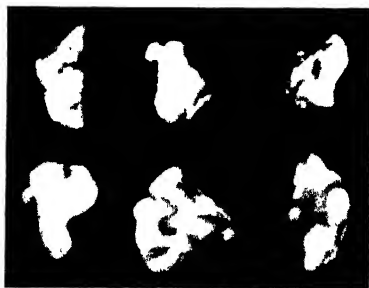
B



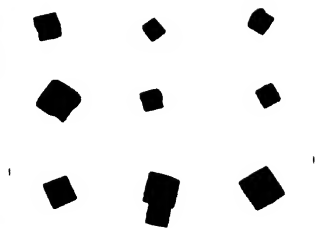
B. LEUCOCASE.

Upper Eocene, Auvers-sur-Oise, in Paris [x 40.]

C



D



C, D. LIMONITE.

- C After Glauconite, I.I. Greensand, Surrey. [x 59.]
 D After Pyrite, Keuper, Yorkshire [x 41.]

LIMONITE [Pl. 21 C, D, facing p. 309.]

Chem. Comp. $\text{Fe}_2\text{O}_3 \cdot n\text{H}_2\text{O}$.

System. Non-crystalline.

Habit. Varied; pseudomorphous after iron-ores.

Structure. Amorphous, earthy.

Fracture. Uneven.

Hardness. $4 \pm$.

Spec. Grav. $3.8 \pm$.

Lustre. Submetallic, dull.

Colour. Dark brown, yellowish-brown.

Mag. Prop. Varies according to degree of alteration of the original mineral from which it was derived; essentially non-magnetic *per se*.

Elect. Prop. Moderate conductor.

Opt. Prop. Opaque. R.I. very high, $n = 2.05 \pm$. Seen occasionally on thin edges of grains.

Characters in Sediments. Of frequent occurrence as irregular grains and as powdery aggregates. It has a brown, ochreous colour by reflected light, being opaque in transmitted light except in very thin sections, when a brownish-yellow colour prevails. The translucent particles are isotropic. Limonitic pseudomorphs after marcasite, pyrite, magnetite and hematite are not uncommon, while its occurrence as a decomposition product of glauconite is often observed. It represents one of the most prevalent forms of authigenous material found in sediments.

Occurrence. Ubiquitous in detrital sediments as a cementing medium.

Possible Sources of Derivation. Iron-ores of varying composition. Iron-bearing minerals.

REMARKS.—Limonite is the commonest coating of detrital particles and its removal, prior to their microscopical analysis, necessitates the usual preliminary treatment of a sample with dilute HCl or alkali. See also goethite, p. 291.

MAGNESITE

Chem. Comp. $\text{MgO} \cdot \text{CO}_2$.

System. Trigonal.

Habit. Prismatic, rhombohedral. Crystals rare.

Structure. Crystalline, massive.

Cleavage. Perfect $\parallel (10\bar{1}1)$.

Fracture. Irregular.

Hardness. $3.5-4$.

Spec. Grav. 2.96 .

Lustre. Pearly, resinous.

Colour. Colourless, white, yellow, brown. Transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low for ϵ , high for ω ; $\epsilon = 1.509$, $\omega = 1.700$. Birefringence very strong, $\omega - \epsilon = 0.191$. Optically uniaxial, negative.

Characters in Sediments. Occurs as quite irregular grains, crystals being rare. Cleavage and "twinkling" on rotation of polariser are characteristic, but the mineral is difficult to distinguish microscopically unless anticipated from other evidence. Distinguished from calcite by absence of lamellar twinning, higher R.I. (for ω), higher birefringence. The S.G. of magnesite is higher than that of

calcite; the latter floats, the former sinks in bromoform (2.9). Physical tests often necessary in confirmation.

Occurrence. Recorded by P. G. H. Boswell.¹

Possible Sources of Derivation. Schists, ultrabasic igneous rocks; magnesite deposits.

REMARKS.—Unlike calcite and dolomite, magnesite is insoluble in cold dilute HCl. Soluble in hot acid.

Reference.

¹ *Proc. Liverpool Geol. Soc.*, 13, 1923, p. 268.

MAGNETITE

(SPINEL GROUP)

Chem. Comp. Fe_3O_4 .

System. Isometric.

Habit. Octahedral, dodecahedral (sometimes with striations || major diagonal of crystal face) or twinned on (111).

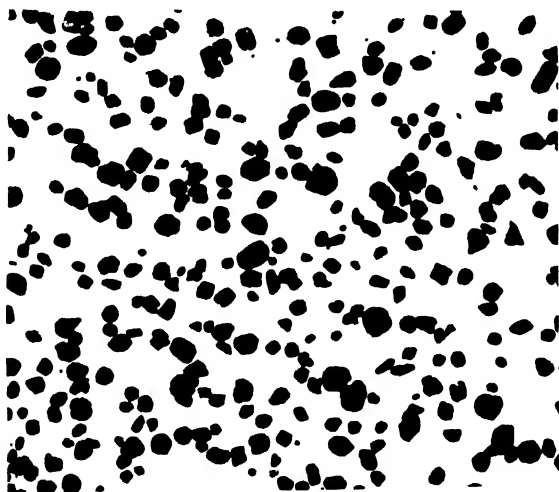


FIG. 83. Magnetite, Alluvial Sand, Colombia, S. America. [x. 20.]

Structure. Crystalline, granular, massive.

Cleavage. None. Parting || (111).

Fracture. Subconchoidal, uneven, hackly.

Hardness. 5.5-6.5.

Spec. Grav. 5.1-5.18.

Lustre. Metallic, submetallic, dull. Grey in vertical reflected light.

Colour. Silver-grey.

Mag. Prop. Strongly magnetic.

Elect. Prop. Good conductor.

Opt. Prop. Opaque. R.I. very high, $n=2.42$.

Characters in Sediments. The octahedral, silver-grey or black crystals of this species are very characteristic, as also are the irregularly shaped, shiny black grains. Careful examination of some grains with powerful incident light and high power objective frequently reveals the presence of minute facets. In the absence of such faceting, the grains may have only a dull grey lustre and be difficult to distinguish from ilmenite (p. 301). Both angular and well rounded irregular grains are also common, the former often showing a marked hackly fracture. Partial alteration to limonite is frequently observed, also to hematite or siderite.

Occurrence. Numerous records extant. The following examples have been confirmed with the bar or electro-magnet and are so recorded by the authors concerned :—in the Upper Lias—Inferior Oolite, West of England;¹ in the Pliocene deposits of Cornwall;² in the later Tertiary deposits of East of England.³ Other occurrences are :—in the Old Red Sandstone of the West Midlands;⁴ in the Bunter Sands of the Midlands;⁵ in the Northampton Ironstone;⁶ in the dune sands of South Wales;⁷ in the Dartmoor detritals;⁸ in the sands of the fore-shore of the Carnarvon coast;⁹ in certain surface deposits of Cambridgeshire.¹⁰

Possible Sources of Derivation. Basic and ultrabasic igneous rocks.

REMARKS.—Less common in sediments than ilmenite. Distinguished from ilmenite by its lustre and crystalline form if developed and may be separated from that mineral by using a horseshoe or bar magnet, which is always the safest preliminary test in diagnosis.

References.

- ¹ P. G. H. Boswell, *Geol. Mag.*, 61, 1924, p. 253.
- ² H. B. Milner, *Quart. Journ. Geol. Soc.*, 78, 1922, p. 354, 358.
- ³ I. S. Double, *Proc. Geol. Assoc.*, 35, 1924, p. 338.
- ⁴ W. F. Fleet, *Geol. Mag.*, 63, 1926, p. 513.
- ⁵ J. B. Scrivenor, *Mineral. Mag.*, 13, 1903, p. 348.
- ⁶ J. G. A. Skerl, *Proc. Geol. Assoc.*, 38, 1927, p. 379.
- ⁷ A. Stuart, *Proc. Geol. Assoc.*, 35, 1924, p. 321.
- ⁸ A. Brammall, *Proc. Geol. Assoc.*, 39, 1928, p. 35.
- ⁹ T. H. Cope, *Proc. Liverpool Geol. Soc.*, 9, 1902, p. 208.
- ¹⁰ R. H. Rastall, *Proc. Cambridge Phil. Soc.*, 17, 1913, p. 132.

MARCASITE

Chem. Comp. FeS₂.

System. Orthorhombic.

Habit. Tabular || (001); pyramidal. Commonly twinned on (110), often repeated; less common on (101); simple crystals rare.

Structure. Crystalline, fibrous, concretionary and radiating.

Cleavage. Poor || (110), imperfect || (011).

Fracture. Uneven, ragged. (Very brittle.)

Hardness. 6-6.5.

Spec. Grav. 4.8.

Lustre. Metallic, splendid. With dark ground illumination, creamy-white.

Colour. Brass-yellow to greyish-yellow.

Mag. Prop. Weakly magnetic.

Elect. Prop. Good conductor.

Opt. Prop. Opaque. "Produces marked rotation of the plane of polarization of reflected light, in which it has a peculiar and characteristic pleochroism" (A. N. Winchell).

Characters in Sediments. Grains usually small, very ragged and possessing a typical greyish-yellow metallic lustre in reflected light; superficial alteration to limonite is commonly shown. Traces of radial structure noted in some examples.

Occurrence. In the Sandgate Beds (Lower Greensand), Gault, Chalk, Woolwich and Reading Beds and London Clay of the Croydon Regional Survey area (Surrey etc.);¹ in the Thanet Beds, Reading Beds and London Clay, N.E. London Basin.²

Possible Sources of Derivation. Metalliferous veins; sedimentary rocks, especially chalk.

REMARKS.—Much less common than its isomer pyrite, being easily decomposed. Molluscan fragments preserved in marcasite sometimes found.²

References.

¹ G. M. Davies, *Proc. and Trans. Croydon Nat. Hist. Soc.*, 1915-16, p. 86.

² P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 71, 1915, p. 577, 581 and table iv.

General Reference.

F. A. Bannister, "The Distinction of Pyrite from Marcasite etc." *Mineral. Mag.*, 23, 1932, p. 179.

MELANITE

(GARNET GROUP)

Chem. Comp. $3\text{CaO} \cdot (\text{Fe}, \text{Ti})_2\text{O}_3 \cdot 3(\text{Si}, \text{Ti})\text{O}_2$.

System. Isometric.

Habit. Dodecahedral, trapezohedral with hexoctahedral modifications.

Structure. Crystalline.

Cleavage. None.

Fracture. Conchoidal.

Hardness. 7.

Spec. Grav. 3.7.

Lustre. Vitreous, resinous. Translucent to opaque.

Colour. Black.

Mag. Prop. Moderately magnetic.

Elect. Prop. Poor conductor.

Opt. Prop. R.I. very high, $n=1.94$. Optically isotropic.

Characters in Sediments. Occurs as black, usually subangular dodecahedral grains, often with characteristic striations || (110).

Occurrence. In the Silurian Rocks of Southern Scotland;¹ in surface deposits derived from disintegration of melanite-syenites of the Assynt district, N.B.²

Possible Sources of Derivation. Metamorphic rocks (contact-altered limestones). Syenite. Acid igneous rocks.

REMARKS.—Melanite is really the black variety of *andradite* (q.v. p. 238) in which titanium replaces in part iron and also silica. The grey-black variety is sometimes known as "*schorlomite*," which may also be considered a variety of andradite.

References.

¹ W. Mackie, *Rep. Brit. Assoc.*, 1928 (Glasgow), 1929, p. 556.

² J. J. H. Teall, "Geology of the N.W. Highlands." *Mem. Geol. Surv. Scotland*, 1907, p. 442.

MICROCLINE

(FELSPAR GROUP)

[Pl. 23 A, B, facing p. 316.]

Chem. Comp. $K_2O \cdot Al_2O_3 \cdot 6SiO_2$.

System. Triclinic.

Habit. Prismatic, frequently twinned according to Carlsbad, Baveno and Manebach laws; also shows fine microscopic lamellar twinning (albite and pericline laws), giving rise to characteristic "cross-hatching." Crystals similar to orthoclase (q.v. p. 321).

Structure. Crystalline, massive.

Cleavage. Distinct $\parallel (001)$, imperfect $\parallel (010)$, more rarely $\parallel (110)$ and $(\bar{2}01)$.

Parting $\parallel (100)$ occasionally seen.

Fracture. Conchoidal, uneven.

Hardness. 6.

Spec. Grav. 2.55.

Lustre. Vitreous.

Colour. White, yellow, green or red. Transparent.

Mag. Prop. Non-magnetic.

Elect. Prop. Bad conductor.

Opt. Prop. R.I. low, $\alpha = 1.522$, $\beta = 1.526$, $\gamma = 1.530$. Birefringence weak, $\gamma - \alpha = 0.008$. Optically biaxial, negative. Optic axial plane nearly $\perp (010)$. $Bxa = X$ inclined at small angle ($< 5^\circ$) to axis a . $Bxo = Z$ nearly $\perp (010)$. $2V = 83^\circ$. (001) flakes give oblique extinction, 16° and (010) flakes give 5° , measured from the trace of (010) and (001) cleavages respectively. (001) plates invariably show characteristic "cross-hatched" structure. Dispersion weak, $\rho > \nu$.

Characters in Sediments. "Platy" basal grains (001) are the most common, easily recognised by the characteristic "cross-hatching" in polarised light. Other forms, such as (010) cleavage fragments, are rarer. In most examples the grains present irregular outlines. Inclusions are sometimes seen; these may be primary muscovite (distinct from that occurring as a decomposition product), zircon, iron-ores or quartz. Decomposition to muscovite or kaolinite renders grains greyish-white by reflected light and causes the appearance of highly polarising aggregates between crossed nicols.

Occurrence. In the Torridon Sandstone of N.W. Highlands and of S.E. Skye, N.B.;¹ in the Malvern quartzite;² in the Old Red Sandstone, Cardiff district;³ in the Old Red Sandstone, West Midlands;⁴ in the Millstone Grit, Yorkshire;⁵ in the Middle Permian sands of Yorkshire;⁶ in the New Red Sandstone, West of England;⁷ in the Northampton Ironstone;⁸ in the Abbotsbury Iron-Ore (Corallian), Dorset;⁹ in the later Tertiary deposits, East of England;¹⁰ in surface deposits of S.E. Devonshire;¹¹ in sands of the Northumberland Coast.¹²

Possible Sources of Derivation. Acid igneous rocks. Metamorphic rocks.

REMARKS. — See also *anorthoclase*, the soda-microcline (p. 241). *Perthite* and *microperthite* are names given to regular intergrowths of microcline (or orthoclase, p. 321) with albite (231). Recorded from the New Red Sandstone of the West of England;¹³ from the Mallee Soil of W. Australia.¹⁴

References.

- ¹ Author's observations: see also *Mem. Geol. Surv. Scotland*. N.W. Highlands, 1907, ch. xvi.
- ² G. S. Sweeting, *Proc. Geol. Assoc.*, 38, 1927, p. 551.
- ³ A. Heard and R. Davies, *Quart. Journ. Geol. Soc.*, 80, 1924, p. 508.
- ⁴ W. F. Fleet, *Geol. Mag.*, 63, 1926, p. 512.
- ⁵ A. Gilligan, *Quart. Journ. Geol. Soc.*, 75, 1919, p. 262.
- ⁶ H. C. Versey, *Proc. Yorks. Geol. Soc.*, 20, 1925, p. 205.
- ⁷ H. H. Thomas, *Quart. Journ. Geol. Soc.*, 75, 1919, p. 239.
- ⁸ J. G. A. Skerl, *Proc. Geol. Assoc.*, 38, 1927, p. 385.
- ⁹ Author's observations.
- ¹⁰ I. S. Double, *Proc. Geol. Assoc.*, 35, 1924, p. 336.
- ¹¹ W. G. Shannon, *Geol. Mag.*, 64, 1927, p. 148.
- ¹² L. Hawkes and J. A. Smythe, *Geol. Mag.*, 68, 1931, p. 345.
- ¹³ H. H. Thomas, *op. cit.*, p. 291.
- ¹⁴ D. A. Carroll, *Journ. Roy. Soc. W. Australia*, 20, 1933-4, p. 100.

General Reference.

H. L. Alling, "The Mineralogy of the Feldspars." *Journ. Geol.*, 31, 1923, p. 282, 353.

MONAZITE [Pl. 22, facing p. 314.]

Chem. Comp. (Ce,La,Di)₂O₃.P₂O₅. Some ThO₂.SiO₂.

System. Monoclinic.

Habit. Small crystals flattened || (100) with varying terminations; also elongated || b or (111).

Structure. Crystalline, granular.

Cleavage. Perfect || (001), good || (100), less common || (010), rarely || (111).

Fracture. Uneven, conchoidal.

Hardness. 5.

Spec. Grav. 4.9-5.3.

Lustre. Vitreous, resinous.

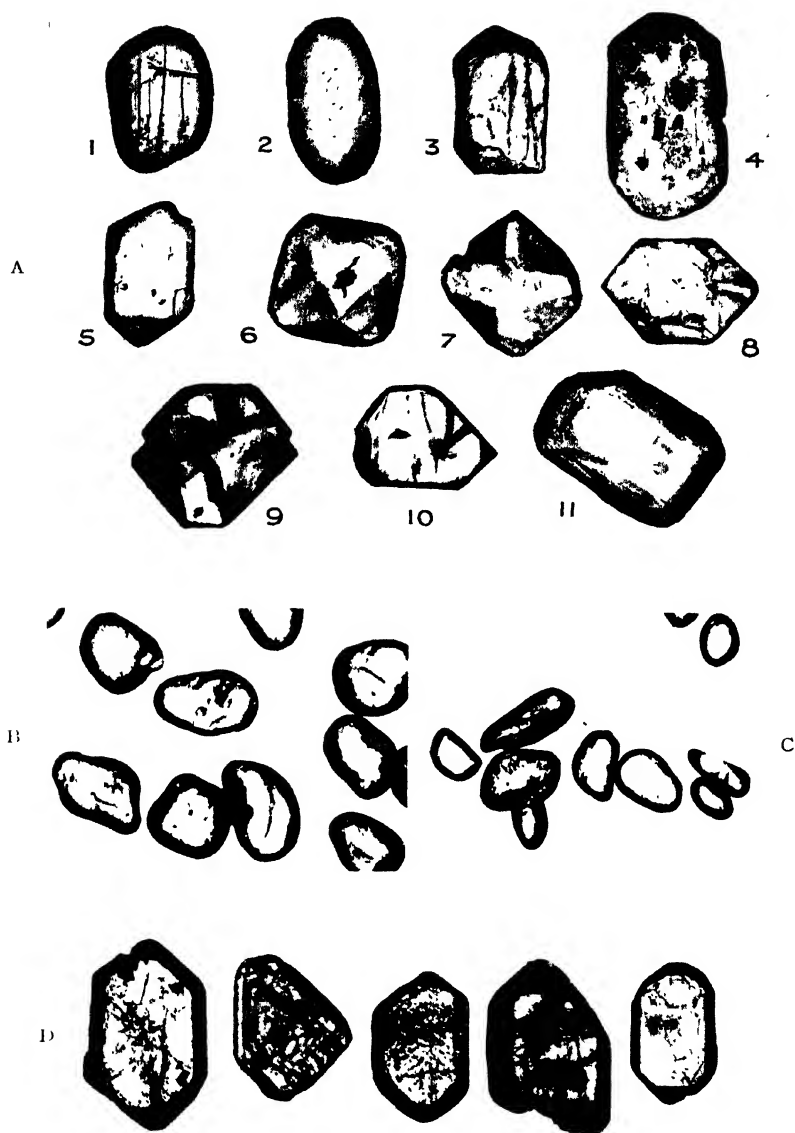
Colour. Yellow, yellowish-brown, brown, red. Translucent to opaque.

Mag. Prop. Weakly magnetic.

Elect. Prop. Bad conductor.

Opt. Prop. R.I. very high, $\alpha = 1.800$, $\beta = 1.801$, $\gamma = 1.849$. Birefringence strong, $\gamma - \alpha = 0.049$. Optically biaxial, positive. Optic axial plane \perp (010), almost || (100). $Bxa = Z$ inclined to principal axis c at angle of 10° . $Y = b$. $2E = 19^\circ$. $2V = 11^\circ$. Varieties without ThO₂.SiO₂ have lower R.I. ($\beta = 1.788$), $X = b$, $Z \wedge c = 2^\circ \pm$. $2V = 14^\circ$, $2E = 25^\circ$. Pleochroism seen in thick grains: $Y = \text{dark yellow} > X = \text{light yellow} = Z = \text{greenish yellow}$. Dispersion weak, $\rho < \nu$.

Characters in Sediments. Usually occurring as well rounded, pale yellow grains with dark border, due to R.I. effect. Colourless, or by contrast, deep brown, almost opaque grains occur. A common detrital form is the rounded, egg-shaped crystal derived from faceted tablets || (100); perfect euhedra, sometimes strongly faceted, are found; (001) cleavage fragments are also frequent: these yield a good posi-



A-D. MONAZITE.

A. 1, 2. Recent Sands, Cape Comorin, Travancore, India. [X 70]
 A. 3-5. Recent Sands, Ceylon. [X 10]
 A. 6-11. Alluvials, Brazil. [X 70]

B. Recent Sand, Travancore, India. [X 43.1]
 C. Shore Sand, Ceylon. [X 45]
 D. Alluvials, Ceylon. [X 12]

To face page 214

PLATE 22

tive interference figure. A. Brammall has described and figured octagonal, hexagonal, quadrilateral and heptagonal crystal habits from the Dartmoor detritals. Decomposition often noted superficially in the form of brown coloured patches or stains which are probably complex alteration products of cerium etc. Inclusions often noted, chiefly gas-filled cavities. A. Brammall states that "Suspensions of opaque dust or brown-red stains are of occasional occurrence; crystal-line inclusions are rare."⁹

Occurrence. In the Millstone Grit of Yorkshire;¹ in the Northampton Ironstone;² in the Ashdown Sands and Fairlight Clays (Wealden) of the Hastings district, Sussex;³ in the Lower Greensand of Surrey;⁴ in the Eocene (?) of Buckland Brewer and the Oligocene of the Bovey Basin, Devonshire;⁵ in the Lenham Beds of Kent etc.;⁶ in the valley deposits derived from the Chipstead and Headley Sands, Surrey;⁷ in Glacial deposits of the Dublin district;⁸ in the Dartmoor detritals.⁹

Possible Sources of Derivation. Acid igneous rocks, especially granites.

REMARKS.—There may be a little difficulty in diagnosing monazite under the microscope and if necessary confirmation may be obtained both chemically and spectroscopically. In the former case the phosphomolybdate reaction is sought and in the latter case the absorption spectrum with the characteristic neodymium-praseodymium bands is easily identified. The use of a spectroscopic eyepiece attachment to the petrological microscope (p. 163) facilitates this observation.

References.

- ¹ A. Gilligan, *Quart. Journ. Geol. Soc.*, 75, 1919, p. 267.
- ² J. G. A. Skerl, *Proc. Geol. Assoc.*, 38, 1927, p. 383.
- ³ H. B. Milner, *Proc. Geol. Assoc.*, 36, 1925, p. 315.
- ⁴ G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915-16, p. 93.
- ⁵ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 79, 1923, p. 226.
- ⁶ G. M. Davies, quoted by P. G. H. Boswell: see *gen. ref.* below.
- ⁷ G. M. Davies, *op. cit.*
- ⁸ F. Smithson, *Geol. Mag.*, 65, 1928, p. 24.
- ⁹ A. Brammall, *Proc. Geol. Assoc.*, 39, 1928, p. 29.

General References.

- F. W. Clarke, "Data of Geochemistry." *U.S. Geol. Surv., Bull.* 770, 5th ed., 1924, p. 359.
 P. G. H. Boswell, *Trans. Geol. Soc. Glasgow*, 18, 1926-27, p. 137.
 C. Raeburn and H. B. Milner, "Alluvial Prospecting." (Murby, London), 1927, p. 405 (for alluvial occurrences, "monazite sands" etc.).

MONTMORILLONITE

(MONTMORILLONITE—BEIDELLITE SERIES)

Chem. Comp. (Mg,Ca)O.Al₂O₃.5SiO₂.(5-8)H₂O (C. S. Ross and E. V. Shannon).

System. ? Orthorhombic. Pseudohexagonal.

Habit. Lamellar aggregates.

Structure. Crystalline.

Cleavage. Perfect || (001).

Fracture. Irregular. Soft.

Hardness. 1.

Spec. Grav. $2.5 \pm$.

Lustre. Pearly.

Colour. White, pink, pale blue, green. Transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low, $\alpha = 1.503$, $\beta = 1.526$, $\gamma = 1.527$. Birefringence moderate, $\gamma - \alpha = 0.024$. Optically biaxial, negative. $Bxa = X$ practically $\perp (001)$. $2V = \text{small}$ (up to 24°).

Characters in Sediments. The essential constituent of many clays, e.g. bentonite (p. 383), Fuller's earth (p. 380), montmorillonite occurs in all stages from incipient alteration of muscovite, glauconite, spodumene etc., to masses of minutely crystalline particles of too small a size to be determined by microscopical means alone. Particles large enough ($5-10\mu$) to be studied optically nearly always show emergence of $bxa \perp$ to flat surface and related properties as above.

Occurrence. In Ordovician altered volcanic material in Iowa, Wisconsin and Missouri, U.S.A.;¹ in Ordovician bentonites of the Eastern United States;² in water-laid volcanic rocks of early Upper Cretaceous age in Arkansas, Oklahoma and Texas.³

Possible Sources of Derivation. Alteration product of feldspar, mica, spodumene, glauconite etc.

REMARKS.—Montmorillonite is a member of a series of hydrated silicates characteristic of certain finely divided sediments such as clays. The series includes *beidellite* (p. 251), *nontronite* (p. 318) and *rillonite*.

References.

¹ V. T. Allen, *Journ. Geol.*, 40, 1932, p. 257.

² C. A. Bonine and A. P. Honess, *Proc. Pennsylvanian Acad. Sci.*, 3, 1929, p. 1.

³ C. S. Ross, H. D. Miser and L. W. Stephenson, *U.S. Geol. Surv., Prof. Paper* 154—F., 1929, p. 175.

General References.

C. S. Ross and E. V. Shannon, "The minerals of bentonite and related clays and their physical properties." *Journ. Amer. Ceram. Soc.*, 9, 1926, p. 77.

C. S. Ross and P. F. Kerr, "The Clay Minerals and their identity." *Journ. Sed. Pet.*, 1, 1931, p. 55.

P. F. Kerr, "Montmorillonite or Smectite as constituents of Fuller's earth and bentonite." *Amer. Min.*, 17, 1932, p. 192.

R. E. Grim, "Petrology of Fuller's Earth Deposits, Olmstead, Illinois." *Econ. Geol.*, 28, 1933, p. 344.

MUSCOVITE

(MICA GROUP) [Pl. 23 C, D, facing p. 316.]

Chem. Comp. $(K, Na)_2O \cdot 3Al_2O_3 \cdot 6SiO_2 \cdot 2H_2O$.

System. Monoclinic, pseudohexagonal.

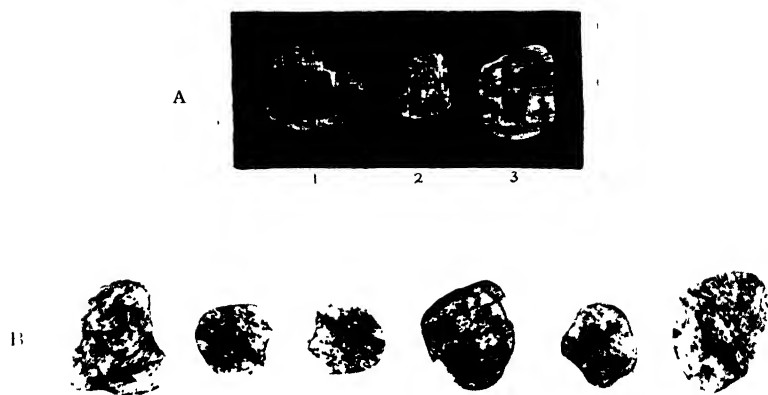
Habit. Tabular crystals $\parallel (001)$. Pseudo-orthorhombic or pseudo-rhombohedral forms found.

Structure. Well laminated, massive; individual crystals rare.

Cleavage. Perfect $\parallel (001)$. Parting $\parallel (010)$ and (111) .

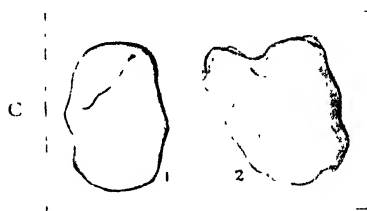
Fracture. Ragged (rare).

Hardness. $2.5-3$.



A, B MICROCLINE. (x *Nicol's*)

- A 1, 2, Forillon Sandstone, Skye, N.B. (x 40)
 A 3, Abbotsbury Iron Ore (Corallian), Abbotsbury, Dorset. (x 40)
 B, Permian, Cumberland. (x 25)



C, D. MUSCOVITE.

- C 1, 2 Kelloways Rock, near Malton, Yorks. (x 65)
 D, Bagshot Sand, Essex. (x 42)

Spec. Grav. 2.76-3.

Lustre. Vitreous, pearly.

Colour. Colourless to yellow, deepening with thickness; grey.

Mag. Prop. Normally non-magnetic, occasionally magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low, $\alpha=1.558$, $\beta=1.595$, $\gamma=1.601$. Birefringence strong, $\gamma-\alpha=0.043$, but that usually seen in cleavage (001) flakes is due to $\gamma-\beta=0.006$ and hence is very weak. Optically biaxial, negative. Optic axial plane $\perp(010)$. $Z=b$. $Bxa=X$ practically $\perp(001)$, hence cleavage plates always yield good interference figure. $2V=40^\circ \pm$. $2E=68^\circ$. Dispersion distinct, $\rho < v$.

Characters in Sediments. Commonly in thin, colourless platy grains (001), with characteristic low R.I., bluish-grey interference tint and good figure. Other forms extremely rare. Grains usually rounded and often from three to four times larger than the average grade-size of associated minerals. Inclusions are common, such as zircon, rutile, tourmaline, apatite, spinel, quartz, iron ores and garnet. Undulose extinction is a feature of some varieties, implying derivation from metamorphic rocks.

Occurrence. In the Torridonian Sandstone, S.E. Skye, N.B.;¹ in the Hollybush Sandstone (Cambrian) of the Malvern district;² in Cambrian shales, Ordovician and Silurian sands, Lower Devonian sandstone of the English Midlands;³ in the May Hill Sandstone (Silurian) of the Malvern district;⁴ in the Downtonian of the West Midlands;⁵ in the Old Red Sandstone of the Cardiff district;⁶ in the Millstone Grit of Yorkshire;⁷ in the Bunter Pebble Bed of the West of England;⁸ in the Keuper Waterstones of Leicestershire;⁹ in the Upper Lias—Inferior Oolite sands of the West of England;¹⁰ in the Kella-ways Rock (Oxfordian) of Yorkshire etc.;¹¹ in the Upper Kimmeridge Clay—Portland Sand of Buckinghamshire etc.;¹² in the Thanet Sands, Reading Beds and London Clay of the N.E. London basin;¹³ in the Pliocene deposits of Cornwall;¹⁴ in the later Tertiary deposits of the East of England;¹⁵ in the Dartmoor detritals.¹⁶

Possible Sources of Derivation. Igneous and metamorphic rocks.

REMARKS.—It is sometimes found that two distinct varieties of muscovite occur in a sediment, one which floats, the other which sinks in bromoform (S.G. 2.9). In such circumstances very careful optical examination of the grains is desirable and may lead to the suspicion of leached biotite in the case of the heavier flakes.

References.

- ¹ Author's observations.
- ² G. S. Sweeting, *Proc. Geol. Assoc.*, 38, 1927, p. 553.
- ³ W. F. Fleet, *Geol. Mag.*, 62, 1925, p. 98.
- ⁴ G. S. Sweeting, *op. cit.*, p. 557.
- ⁵ W. F. Fleet, *Geol. Mag.*, 63, 1926, p. 512.
- ⁶ A. Heard and R. Davies, *Quart. Journ. Geol. Soc.*, 80, 1924, p. 499.
- ⁷ A. Gilligan, *Quart. Journ. Geol. Soc.*, 75, 1919, p. 263.
- ⁸ H. H. Thomas, *Quart. Journ. Geol. Soc.*, 58, 1902, p. 626.
- ⁹ T. O. Bosworth, "Keuper Marls around Charnwood." *Leicester Lit. and Phil. Soc.*, 1913, p. 93.
- ¹⁰ P. G. H. Boswell, *Geol. Mag.*, 61, 1924, p. 252.
- ¹¹ Author's observations.
- ¹² E. Neaverson, *Proc. Geol. Assoc.*, 36, 1925, p. 251.
- ¹³ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 71, 1915, p. 576, 578, 581.
- ¹⁴ H. B. Milner, *Quart. Journ. Geol. Soc.*, 78, 1922, p. 358.
- ¹⁵ I. S. Double, *Proc. Geol. Assoc.*, 35, 1924, p. 341.
- ¹⁶ A. Brammall, *Proc. Geol. Assoc.*, 39, 1928, p. 46.

NEPHRITE(Syn. JADE, Var. TREMOLITE OR ACTINOLITE, *q.v.* p. 229, 349)**NONTRONITE (Chloropal)**

(MONTMORILLONITE—BEIDELLITE SERIES)

Chem. Comp. $(\text{Fe}, \text{Al})_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot 2\text{H}_2\text{O}$. Also with Ca, Mg.**System.** Monoclinic.**Habit.** Prismatic, fibrous.**Structure.** Crystalline, compact, earthy.**Cleavage.** Perfect $\parallel (001)$.**Fracture.** Irregular. Soft.**Hardness.** 1.**Spec. Grav.** 2.5.**Lustre.** Pearly.**Colour.** Green, olive green, yellow, orange. Translucent.**Mag. Prop.** ?**Elect. Prop.** ?**Opt. Prop.** Variable with composition. R.I. moderate, $\alpha = 1.585$, $\beta = 1.593$, $\gamma = 1.603$. Birefringence moderate, $\gamma - \alpha = 0.023$. Optically biaxial, negative. $Bxa = X$ nearly (?) $\perp (001)$. $Bxo = Z$ nearly (?) \parallel elongation of fibres (*A. N. Winchell*). $X \perp$ cleavage. $2V = 26^\circ \pm$. $2E = 42^\circ \pm$. When pleochroic, $X =$ pale yellow, $Y =$ olive green, $Z =$ yellow to bright green.**Characters in Sediments.** Occurs as green, yellow or orange, prismatic grains of moderate R.I. and characteristic pleochroism (when developed). The optical properties are liable to vary with the degree of alteration which the parent mineral has undergone.**Occurrence.** Ball clay, china clay, ordinary clay and Fuller's earth.**Possible Sources of Derivation.** Alteration product of igneous rocks.**REMARKS.**—Nontronite is a member of a series of hydrated ferrous-aluminous silicates characteristic of certain finely divided sediments such as clays. The series includes *montmorillonite* (p. 315), *beidellite* (p. 251), *rillonite* etc.**General References.**B. C. Renick, "Base Exchange in Ground Water by Silicates, as illustrated in Montana." *U.S. Geol. Surv., Water Supply Paper* 520—D, 1924.W. Noll, "Zur Kenntnis des Nontronits." *Chem. Erde*, 5, 1930, p. 373.C. S. Ross and P. F. Kerr, "The Clay Minerals and their Identity." *Journ. Sed. Pet.*, 1, 1931, p. 55.**OLIGOCLASE**

(PLAGIOCLASE FELSPAR GROUP)

Chem. Comp. Ab_4An .**System.** Triclinic.**Habit.** Lamellar, massive. Crystals rare. Commonly twinned about (010) (Albite law); other types according to Carlsbad (c axis), pericline (b axis), Baveno (021) and Manebach (001) laws.**Structure.** Crystalline,

Cleavage. Perfect \parallel (001), distinct \parallel (010), imperfect \parallel (110).

Fracture. Conchoidal, irregular.

Hardness. 6.

Spec. Grav. 2.64.

Lustre. Vitreous, pearly.

Colour. White, grey, green. Sometimes faintly iridescent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low, $\alpha = 1.539$, $\beta = 1.543$, $\gamma = 1.547$. Birefringence weak, $\gamma - \alpha = 0.008$. Optically biaxial, negative. Optic axial plane nearly \parallel (010). $Bxa = X \wedge (001) = 1^\circ - 6^\circ$. $\wedge(010) = 1^\circ - 15^\circ$. $2V = 86^\circ$. Dispersion weak, $\rho < \nu$.

Characters in Sediments. Detrital oligoclase appears from the records to be the most common member of the plagioclase feldspar group to be found in sediments. It seldom, if ever, presents crystal faces, irregular shaped grains being determined by (001) and (010) cleavages, usually with characteristic twin lamellæ from which extinction angles may be measured. Identification is based on these, on lower R.I. than Canada balsam and on a tendency to show little or no alteration.

Occurrence. In the Torridonian Sandstone of the N.W. Highlands¹ and of S.E. Skye;² in the May Hill Sandstone (Silurian) of the Malvern district;³ in the Old Red Sandstone of the West Midlands;⁴ in the Millstone Grit of Yorkshire;⁵ in the Northampton Ironstone;⁶ in the later Tertiary deposits of East England;⁷ in the Dartmoor detritals;⁸ in the Mallee soil of Western Australia.⁹

Possible Sources of Derivation. Igneous rocks, in particular acid types. Also gneiss and schist.

References.

- ¹ J. J. H. Teall, "Geology of the N.W. Highlands." *Mem. Geol. Surv. Scotland*, 1907, ch. xvi, p. 285.
- ² Author's observations.
- ³ G. S. Sweeting, *Proc. Geol. Assoc.*, 38, 1927, p. 557.
- ⁴ A. Heard and R. Davies, *Quart. Journ. Geol. Soc.*, 80, 1924, p. 499.
- ⁵ A. Gilligan, *Quart. Journ. Geol. Soc.*, 75, 1919, p. 262.
- ⁶ J. G. A. Skerl, *Proc. Geol. Assoc.*, 38, 1927, p. 385.
- ⁷ I. S. Double, *Proc. Geol. Assoc.*, 35, 1924, p. 336.
- ⁸ A. Brammall, *Proc. Geol. Assoc.*, 39, 1928, p. 46.
- ⁹ D. A. Carroll, *Journ. Roy. Soc. West Australia*, 20, 1933-4, p. 100.

General Reference.

- H. L. Alling, "The Mineralogy of the Feldspars." *Journ. Geol.*, 21, 1923, p. 282, 353.

OLIVINE (Chrysolite)

(OLIVINE GROUP)

[Pl. 24 A, B, facing p. 325.]

Chem. Comp. $2(\text{Mg,Fe})\text{O} \cdot \text{SiO}_2$.

System. Orthorhombic.

Habit. Flattened prismatic crystals \parallel (100) or (010) with bipyramidal and basal terminations. Sometimes twinned on (011), rarely on (012).

Structure. Crystalline, granular, massive.

Cleavage. Poor \parallel (010) and (100).

Fracture. Conchoidal.

Hardness. 6·5-7.

Spec. Grav. 3·27-3·37.

Lustre. Vitreous, resinous.

Colour. Green, olive green, dark green, brown.

Mag. Prop. Weakly magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. high, $\alpha=1\cdot653$, $\beta=1\cdot670$, $\gamma=1\cdot689$. Birefringence strong, $\gamma-\alpha=0\cdot036$. Optically biaxial, positive. Optic axial plane $\parallel(001)$. $Bxa=Z=a \perp(100)$. $X=b$. $Y=c$. Straight extinction with prismatic grains. $2V=88^\circ$. Non-pleochroic. Dispersion weak, $\rho<v$. With greater than 12 per cent. FeO, olivine is negative and the value for $2V$ exceeds 90° ; the R.I. is also higher, e.g. $\beta=1\cdot705$.

Characters in Sediments. Usually occurs as irregularly shaped and much fractured grains, showing traces of decomposition to antigorite or chrysotile along one or more prominent cracks, frequently accentuated by hematite, limonite or goethite. Well preserved euhedra sometimes met with (Pl. 24). The normal colour tends to be bleached to a yellowish-green tint in sediments. Grains are often due to (010) or (100) cleavages and frequently show positive biaxial interference figure, with large optic axial angle. (N.B.—Most olivine is positive.) Note vivid polarisation colours.

Occurrence. In shore sands, Cape Verde Islands (beautiful euhedra);¹ in shore sands, Kynance Cove, S. Cornwall;² in the North Sea Drift and Upper Glacial Brick-earths, East Anglia;³ in sands of the Northumberland coast;⁴ in sand at Duntulm, Skye.⁵

Possible Sources of Derivation. Basic and ultrabasic igneous rocks: gabbros, dolerites, peridotites etc.

REMARKS.—A comparatively rare detrital mineral, usually found in recent deposits (such as shore sands or dune sands) occurring in the vicinity of ultrabasic rock masses. See also *fayalite*, p. 284.

References.

¹ G. M. Part's observations.

² Author's observations.

³ P. G. H. Boswell, *Proc. Geol. Assoc.*, 27, 1916, p. 79.

⁴ L. Hawkes and J. A. Smythe, *Geol. Mag.*, 68, 1931, p. 345.
F. Walker, *Trans. Edinburgh Geol. Soc.*, 12, 1932, p. 321.

OMPHACITE

(VARIETY OF DIOPSIDE, *q.v.* p. 277)

OPAL

Chem. Comp. $\text{SiO}_2 \cdot n\text{H}_2\text{O}$.

System. Amorphous.

Habit. Layers; botryoidal, stalactitic.

Structure. Massive, compact.

Cleavage. None.

Fracture. Conchoidal. Brittle.

Hardness. 6±.

Spec. Grav. 2·1±.

Lustre. Vitreous, porcellaneous, resinous.

Colour. White, milky. More rarely with brilliant play of colours (precious opal). Translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low, $n = 1.406 \pm$. Isotropic; sometimes exhibits polarisation colours due to strain.

Characters in Sediments. Opal is uncommon in sediments, but when identified under the microscope, it exhibits characteristic porcelain white, shapeless grains in reflected light, with R.I. much lower than Canada balsam, resulting in bold relief. Grains displaying colour are extremely rare. Independent determinations of S.G. and R.I. should always be made.

Occurrence. In the Suffolk Boxstones;¹ in the Guedan (Middle Tertiary) formation of South-Western Texas, U.S.A.;² in Siliceous Shale (Miocene or Pliocene) of Southern California, U.S.A.³

Possible Sources of Derivation. Decomposed igneous rocks. Siliceous deposits.

REMARKS.—A rare, glass-clear form known as *hyalite* has been recorded from sediments.

References.

¹ P. G. H. Boswell, *Geol. Mag.*, 1915, p. 250.

² T. L. Bailey, *Univ. Texas Bull.* 2645, 1926, p. 1.

³ R. D. Reed, *Journ. Geol.*, 36, 1928, p. 342.

General References.

P. G. H. Boswell, "Some Aspects of the Petrology of Sedimentary Rocks." *Proc. Liverpool Geol. Soc.*, 13, 1923, p. 268.

T. C. Wollaston, "Opal: The Gem of the Never Never." (Murby, London), 1928.

ORTHITE

(Syn. ALLANITE, *q.v.* p. 232)

ORTHOCLASE

(FELSPAR GROUP)

Chem. Comp. $K_2O \cdot Al_2O_3 \cdot 6SiO_2$.

System. Monoclinic.

Habit. Prismatic, often twinned according to the Carlsbad (001) or less commonly Baveno (021) laws.

Structure. Crystalline.

Cleavage. Perfect || (001), good || (010), imperfect || (110).

Fracture. Conchoidal.

Hardness. 6.

Spec. Grav. 2.56.

Lustre. Vitreous.

Colour. Colourless, grey or reddish-white

Elect. Prop. Non-conductor.

Mag. Prop. Non-magnetic.

Opt. Prop. R.I. low, $\alpha=1.518$, $\beta=1.524$, $\gamma=1.526$. Birefringence weak, $\gamma-\alpha=0.008$. Optically biaxial, negative. Optic axial plane $\perp(010)$. $Bxa=X$ inclined at 85° to (001) or 5° (with a basal cleavage trace) in (010) . $Bxo=Z \perp(010)$. Y or $Z=b$. (001) plates show straight extinction, (010) plates give extinction angle of 5° . $2V=0^\circ-70^\circ$. $2E=0^\circ-122^\circ$. Dispersion weak, $\rho>v$.

Characters in Sediments. Irregularly shaped grains flattened $\parallel(001)$ are the usual types met with in the "lighter" portions of clastic sediments. Secondary muscovite (sericite) or kaolinite clouding the grains is a common feature and in these types aggregate polarisation will usually be noted. Rectangular grains showing definite Carlsbad twinning are sometimes met with; these are accordingly easy to diagnose. Distinction from quartz, where such twinning is absent, is sometimes a matter of difficulty, but R.I. test ($<$ Canada balsam) is usually positive. Inclusions common, quartz, mica, iron-ores, rutile and zircon being observed.

Occurrence. In the Torridonian Sandstones of the N.W. Highlands of Scotland;¹ of S.E. Skye;² in the May Hill Sandstone (Silurian), Malvern district;³ in the Old Red Sandstone of the West Midlands⁴ and of the Cardiff district;⁵ in the Millstone Grit of Yorkshire;⁶ in the Upper Lias—Lower Inferior Oolite of the West of England;⁷ in the Reading Beds (Eocene) of the N.E. London Basin;⁸ in the Eocene of Haldon and the Oligocene sands of Bovey Tracey, Devonshire;⁹ in the Pliocene of Cornwall;⁹ in deposits of doubtful age, Lustleigh Cleave, Devonshire (in which the mineral is recorded as "ultra-dominant");⁹ in the dune sands of South Wales;¹⁰ in the Dartmoor detritals;¹¹ in the Lappa Sand (soil deposit) of King Island, Tasmania.¹²

Possible Sources of Derivation. Acid igneous rocks, pegmatite veins.

REMARKS.—*Adularia* is a clear, colourless, orthoclase characterised by short prismatic crystals (110) terminated by (001) and ($\bar{1}01$). *Anorthoclase* is the triclinic, soda-potash feldspar (p. 241). *Perthite* and *microperthite* are names given to regular intergrowths of orthoclase (or microcline, p. 313) and albite (p. 231). *Sanidine* is a tabular, glassy type (010), or elongated $\parallel a$ with (001) termination, found chiefly in sediments derived from volcanic rocks.

References.

- ¹ J. J. H. Teall, "Geology of N.W. Highlands." *Mem. Geol. Surv., Scotland*, 1907, p. 278.
- ² Author's observations.
- ³ G. S. Sweeting, *Proc. Geol. Assoc.*, 38, 1927, p. 557.
- ⁴ W. F. Fleet, *Geol. Mag.*, 63, 1926, p. 512.
- ⁵ A. Heard and R. Davies, *Quart. Journ. Geol. Soc.*, 80, 1924, p. 511.
- ⁶ A. Gilligan, *Quart. Journ. Geol. Soc.*, 75, 1919, p. 262.
- ⁷ P. G. H. Boswell, *Geol. Mag.*, 61, 1924, p. 258.
- ⁸ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 71, 1915, p. 579 and table iv.
- ⁹ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 79, 1923, p. 226.
- ¹⁰ A. Stuart, *Proc. Geol. Assoc.*, 35, 1924, p. 324.
- ¹¹ A. Brammall, *Proc. Geol. Assoc.*, 39, 1928, p. 46.
- ¹² D. A. Carroll, *Journ. Roy. Soc., West Australia*, 20, 1933-4, p. 99.

General Reference.

H. L. Alling, "The Mineralogy of the Feldspars." *Journ. Geol.*, 31, 1923, p. 282, 353. See also Bibliography under W. Mackie (p. 627).

OTTRELITE

(CHLORITOID—OTTRELITE GROUP)

Chem. Comp. $(\text{Fe}, \text{Mn})\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{SiO}_2 \cdot \text{H}_2\text{O}$.**System.** Monoclinic (pseudo-hexagonal) or triclinic.**Habit.** Similar to mica. Curved crystals.**Structure.** Crystalline, radiating aggregates, laminated.**Cleavage.** Perfect $\parallel (001)$.**Fracture.** Irregular.**Hardness.** 7.**Spec. Grav.** 3.3.**Lustre.** Pearly.**Colour.** Grey, green.**Mag. Prop.** Weakly magnetic.**Elect. Prop.** Non-conductor.**Opt. Prop.** R.I. high, $\beta = 1.73$. Birefringence moderate, $\gamma - \alpha = 0.010$.Optically biaxial, positive. Optic axial plane nearly $\parallel (010)$. $Bxa = Z \wedge 3^\circ - 30^\circ \perp (001)$. $Y \wedge b = 0^\circ \pm$. Optic axial angle variable. Pleochroism: X = olive green, Y = blue, Z = yellow-green. Distinct horizontal dispersion, $\rho > v$.**Characters in Sediments.** A much rarer occurrence in detrital sediments than its closely allied species *chloritoid* (p. 265). Characterised by micaceous habit, colour, high R.I., biaxial positive character and distinctive pleochroism. Frequently contains carbonaceous inclusions symmetrically arranged; also quartz, iron ores.**Occurrence.** In the Limburg Loess.¹**Possible Sources of Derivation.** Crystalline schists and phyllites.**REMARKS.**—See also *chloritoid*, p. 265.**Reference.**¹ J. H. Druif, "Over het ontstaan der Limburgsche Loess in verband met haar mineralogische Samenstelling." *Utrecht*, 1927.**General Reference.**H. D. Hedberg, *Journ. Paleont.*, 2, 1928, p. 32.**PENNINITE**

(CHLORITE GROUP)

Chem. Comp. $5(\text{Mg}, \text{Fe})\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{SiO}_2 \cdot 4\text{H}_2\text{O}$.**System.** Monoclinic.**Habit.** Lamellar, platy (001). Twinned on (001) and (110).**Structure.** Crystalline, granular, scaly, radiating.**Cleavage.** Perfect $\parallel (001)$, flexible flakes.**Fracture.** None.**Hardness.** 2.5.**Spec. Grav.** $2.7 \pm$.**Lustre.** Pearly.**Colour.** Green. Translucent to opaque.**Mag. Prop.** Weakly magnetic.**Elect. Prop.** Non-conductor.**Opt. Prop.** R.I. low, $\alpha = 1.576$, $\beta = 1.576$, $\gamma = 1.579$. Birefringence weak, $\gamma - \alpha = 0.003$. Optically biaxial, positive. Optic axial plane $\parallel (010)$. $Bxa = Z \perp (001)$. $Y = b$. Optic axial angle small, $2E = 0^\circ \pm$. Dis-

persion strong, $\rho < v$. Some varieties present pseudo-hexagonal characteristics with uniaxial positive interference figure; more rarely uniaxial negative. A biaxial negative form is also known. Most grains exhibit abnormal "ultra-blue" interference tints. Pleochroism: $(+)X = \text{green} = Y = \text{green} > Z = \text{yellow-green}$; $(-)X = \text{yellow-green} < Y = \text{green} = Z = \text{green}$.

Characters in Sediments. Detrital penninite *per se* is rare (see under *chlorite group*, p. 264). When identified it is usually in the form of (001) flakes or "shreds," distinguished by colour, low R.I. positive (or negative) interference figure and "ultra-blue" polarisation tint.

Occurrence. In the Millstone Grit, Huddersfield;¹ in the Eocene Tejon formation, California, U.S.A.²

Possible Sources of Derivation. Alteration product of ferromagnesian minerals. Decomposed igneous rocks.

REMARKS. — See also *antigorite* (p. 242), *clinochlore* (p. 268) and *delessite* (p. 273).

References.

¹ D. A. Wray and S. Melmore, *Proc. Yorks. Geol. Soc.*, 22, 1931, p. 31.

² A. O. Woodford, *Univ. California Publ., Bull. Dept. Geol. Sci.*, 15, no. 7, 1925, p. 159.

PERICLASE

Chem. Comp. MgO.

System. Isometric.

Habit. Cubes, octahedra.

Structure. Crystalline, granular.

Cleavage. Perfect || (100), poor || (111).

Fracture. Uneven.

Hardness. 5.

Spec. Grav. 3.6.

Lustre. Vitreous.

Colour. Colourless, grey, yellow, dark green, transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. high, $n = 1.736$, optically isotropic.

Characters in Sediments. Occurs as colourless, yellow or dark green grains characterised by high R.I. and perfect cubic cleavage. It is a very rare detrital mineral to be anticipated only in favourable associations, e.g. forsterite, magnesite, spinel. Periclase is unstable, readily changing to brucite ($\text{MgO} \cdot \text{H}_2\text{O}$), hydromagnesite etc.

Possible Sources of Derivation. Contact-altered magnesian limestones.

PHLOGOPITE

(MICA GROUP)

Chem. Comp. $2\text{K}_2\text{O} \cdot 10(\text{Mg}, \text{Fe})\text{O} \cdot 3\text{Al}_2\text{O}_3 \cdot 12\text{SiO}_2 \cdot 3\text{H}_2\text{O}$.

System. Monoclinic (pseudo-hexagonal).

Habit. Tabular, six-sided prisms with well developed basal planes.

Twinned on (110) in thin (001) laminae.

Structure. Lamellar.

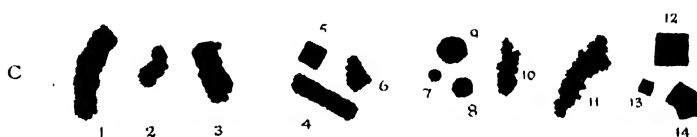
Cleavage. Perfect || (001).



A, B. OLIVINE.

A 1-4 Short Sand, Cape Verde Is. [x 35.]

B Tule Lake, Oregon U.S.A. [x 22.]



D



C, D. PYRITE.

C 1-3. Wadhurst Clay, Southborough, Kent. [x 35.]

C 4-6. Miocene Clay, Trinidad, B.W.I. [x 35.]

C 7-10. Middle Lias Ironstone, Cleveland, Yorkshire. [x 35.]

C 11. Corallian Clay, Weymouth, Dorset. [x 35.]

C 12-14. Weald Clay, Groombridge, Sussex. [x 35.]

D. Gault, Copt Pt., Folkestone. *Reflected light.* [x 36.]

Fracture. Uneven.

Hardness. 3-4.

Spec. Grav. 2·8-3·3.

Lustre. Pearly, submetallic on cleavage planes.

Colour. Brown.

Mag. Prop. Moderately magnetic.

Elect. Prop. Moderate conductor.

Opt. Prop. R.I. low, $\alpha = 1·551$, $\beta = 1·598$, $\gamma = 1·598$. Birefringence strong, $\gamma - \alpha = 0·047$. Optically biaxial, negative. Optic axial plane || (010). $Bxa = X$ nearly \perp (001). $2V = 3^\circ$ or zero. $2E = 5^\circ - 70^\circ$. Pleochroism: $X =$ colourless $< Y =$ brownish-yellow \leq brownish-yellow; or with increase of iron colours may be darker and $X < Z < Y$. Dispersion weak, $\rho < \nu$.

Characters in Sediments. Usually occurs in shapeless grains or flakes of brown or copper-brown colour characterised by higher R.I. than ordinary biotite, by distinctive pleochroism and tendency to acicular inclusions sometimes orientated along lines traversing each other about 60° (asterism). Inclusions are usually iron ores, rutile, tourmaline. Pleochroic halos round inclusions are most uncommon in phlogopite, by contrast with biotite.

Occurrence. In the Thanet Beds of the North-Eastern part of the London Basin.¹

Possible Sources of Derivation. Contact-metamorphosed limestone and dolomite; dedolomitised impure dolomite. Rare in igneous rocks.

Reference.

¹ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 71, 1915, p. 536.

PHOSPHORITE

See Apatite, p. 243, also p. 418.

PICOTITE

(SPINEL GROUP)

Chem. Comp. $(Mg, Fe)O, (Al, Fe, Cr)_2O_3$.

System. Isometric.

Habit. Octahedral, irregular, granular.

Structure. Crystalline.

Fracture. Conchoidal.

Hardness. 8.

Spec. Grav. 4·08.

Lustre. Vitreous to dull metallic.

Colour. "Coffee-brown," yellowish-brown or greenish-brown. Translucent, sometimes opaque.

Mag. Prop. Moderately magnetic.

Elect. Prop. Good conductor.

Opt. Prop. R.I. very high, $n = 2·05 \pm$. Opaque or exhibiting a greenish-brown translucency, when isotropism is noted.

Characters in Sediments. Usually occurring as rolled octahedral grains of dark but characteristic "coffee" colour, much resembling chromite, from which it is not always easily distinguishable microscopically.

Occurrence. Reading Beds (Lower Eocene) of the London Basin;¹ in the shore sands of Mullion Cove and elsewhere along the West coast of the Lizard, Cornwall (proximity to serpentine masses).²

Possible Sources of Derivation. Similar to chromite: basic and ultrabasic igneous rocks, especially serpentine rocks; crystalline schists.

REMARKS.—As might be expected, picotite as a detrital mineral is of very restricted occurrence; it is practically confined to localised (geologically) recent deposits.

References.

¹ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 71, 1915, p. 578.

² Author's observations.

PIEDMONTITE

(EPIDOTE GROUP)

Chem. Comp. $4(\text{Ca}, \text{Mn})\text{O} \cdot 3(\text{Al}, \text{Fe}, \text{Mn})_2\text{O}_3 \cdot 6\text{SiO}_2 \cdot \text{H}_2\text{O}$.

System. Monoclinic.

Habit. Like epidote (p. 282); elongated || b. May be twinned about (100).

Structure. Crystalline.

Cleavage. Perfect || (001).

Fracture. Uneven.

Hardness. 6.5.

Spec. Grav. 3.45-3.5.

Lustre. Vitreous, resinous.

Colour. Reddish-brown, black. Translucent to opaque.

Mag. Prop. Weakly magnetic.

Elect. Prop. Moderate conductor.

Opt. Prop. R.I. very high, $\alpha = 1.750$, $\beta = 1.782$, $\gamma = 1.832$. Birefringence strong, $\gamma - \alpha = 0.082$. Optically biaxial, positive. Optic axial plane || (010). $Bxa = X\Lambda = 7^\circ \pm$. $Bxo = Z\Lambda(001)$ cleavage $= 32^\circ \pm$. $Y = b$. $2V = 55^\circ - 80^\circ$. Inclined and strong dispersion, $\rho > v$. Pleochroism: $X = \text{yellow or orange-yellow} > Y = \text{violet or pink} > Z = \text{red}$. Biaxial negative forms also known with larger axial angle (near 90°).

Characters in Sediments. Grains are usually quite irregular in shape, of a strong reddish-brown to blackish-brown colour, characterised by high R.I., birefringence and distinctive pleochroism. The mineral is generally positive, thus differing from epidote.

Occurrence. In Pliocene sands from borings at Fisrenco, Italy;¹ in shore sands of the Adriatic;² in the Limburg Loess;³ in soils of the U.S.A.⁴

Possible Sources of Derivation. Metamorphic rocks, schist, gneiss. Acid volcanic rocks

REMARKS.—Confirmatory test for manganese is desirable where possible.

References.

¹ E. Repossi, *Atti R. Accad. Sci. Torino*, 63, 1928, p. 223.

² E. Artini, *Rend. R. Ist. lomb.*, 29, 1896, p. 800.

³ J. H. Druif, "Over het ontstaan der Limburgsche Löss in verband met haar mineralogische Samenstelling," *Utrecht*, 1927.

⁴ W. H. Fry, *Econ. Geol. [Letter]*, 10, 1915, p. 292.

PLAGIOCLASE FELSPAR

See Varieties :—

Albite (p. 231).
 Andesine (p. 238).
 Anorthite (p. 241).
 Bytownite (p. 257).
 Labradorite (p. 305).
 Oligoclase (p. 318).

PSILOMELANE

Chem. Comp. Hydrated oxide of manganese. Ba and K sometimes present.

System. Amorphous.

Habit. Massive.

Structure. Botryoidal, reniform, stalactitic.

Cleavage. None.

Fracture. Smooth.

Hardness. 5-6.

Spec. Grav. 4.2.

Lustre. Sub-metallic, dull.

Colour. Grey, black.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. Opaque.

Characters in Sediments. Irregular, steel-grey grains with smooth surface and dull metallic lustre. Difficult of diagnosis by microscopical means alone.

Occurrence. Tertiary and Pleistocene deposits of Colorado County, Texas, U.S.A.¹

Possible Sources of Derivation. Sedimentary rocks as result of direct precipitation. Residual deposits. Manganese-bearing minerals and silicates. Lode minerals.

REMARKS.—Chemical test for Mn always desirable. Comparatively rare mineral in sediments and particularly in British sedimentary rocks of pre-Pleistocene age.

Reference.

¹ T. L. Bailey, *Univ. Texas Bull.* 2333, 1923.

General Reference.

P. G. H. Boswell, *Proc. Liverpool Geol. Soc.*, 13, 1923, p. 268.

PYRITE [Pl. 24 c, D, facing p. 325.]

Chem. Comp. FeS₂.

System. Isometric.

Habit. Cubic, dodecahedral, "pyritohedral" and combinations of different forms. Often twinned (interpenetrant); cubic faces frequently striated || edge (100) (210).

Structure. Crystalline, massive.

Cleavage. Poor || (100) and (111).

Fracture. Conchoidal, uneven; brittle,

Hardness. 6-6.5.

Spec. Grav. 4.8-5.1.

Lustre. Metallic, splendid.

Colour. Brass-yellow, sometimes tarnished.

Mag. Prop. Non-magnetic.

Elect. Prop. Good conductor.

Opt. Prop. Opaque.

Characters in Sediments. Commonly occurs in well crystallised dodecahedra or "pyritohedra," the latter often in complex interpenetration. Other forms are nodular, botryoidal; sometimes masses of minute crystals unite to produce aggregates of fantastic appearance, especially when the mineral is intimately associated with lignite, as in clays, or with asphaltic limestones. The brass-yellow colour by oblique dark ground and creamy-white colour by vertical illuminations, are very characteristic, as is also the tarnish (a dull blackish-brown veneer) due to alteration, probably to limonite. Simple cubic grains are rare.

Occurrence. In most argillaceous rocks, especially Jurassic and Cretaceous clays in England. Prolific in many of the Cambrian, Ordovician and Silurian shales of Wales and the Welsh borderland;¹ in the Devonian and Culm Beds of the Torquay district;² in the Permian rocks of the Torquay Promontory;³ in the Northampton Ironstone;⁴ in the Fairlight Clays of Fairlight, Sussex;⁵ in the Wadhurst Clay (Wealden) generally;⁶ in the Weald Clay, Atherfield Clay, Sandgate Beds (Lower Greensand), Woolwich and Reading loams, London Clay of the Croydon Regional Survey area (Surrey etc.);⁷ in the Dartmoor detritals.⁸

Possible Sources of Derivation. Igneous and sedimentary rocks, metaliferous veins; chiefly authigenic.

REMARKS.—Pyrite is more common in detrital sediments than its isomer marcasite (p. 311) except in certain local cases. It may be removed from residues (if necessary) by boiling with weak HNO_3 , or a better method is to use 100 vol. hydrogen peroxide, which has the advantage of not attacking many minerals which are liable to reaction with acid.

References.

¹ Author's observations.

² W. G. Shannon, *Proc. Geol. Assoc.*, 39, 1928, p. 137.

³ W. G. Shannon, *Proc. Geol. Assoc.*, 38, 1927, p. 133.

⁴ J. G. A. Skerl, *Proc. Geol. Assoc.*, 38, 1927, p. 380.

⁵ H. B. Milner, *Proc. Geol. Assoc.*, 36, 1925, p. 315.

⁶ Author's observations.

⁷ G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915-16, p. 82.

⁸ A. Brammall, *Proc. Geol. Assoc.*, 39, 1928, p. 35.

PYROLUSITE

Chem. Comp. MnO_2 .

System. Amorphous (?Orthorhombic).

Habit. Probably pseudomorphous after manganite ($\text{Mn}_2\text{O}_3 \cdot \text{H}_2\text{O}$).

Structure. Normally amorphous, massive.

Cleavage. None.

Fracture. Splintery, uneven.

Hardness. 2-2.5.

Spec. Grav. 4.75.

Lustre. Metallic, dull.

Colour. Purplish-black.

Mag. Prop. Weakly magnetic.

Elect. Prop. Moderate conductor.

Opt. Prop. Opaque.

Characters in Sediments. Usually occurs in the form of irregular purplish or dead black grains, void of all crystalline structure. P. G. H. Boswell thus notes one occurrence: "It has a flat irregular and angular form, is dull black by reflected light, but sometimes shows striations or flutings characteristic of the mineral."³

Occurrence. In the Fairlight Clays (Wealden) of Sussex;¹ in the Chalk of Surrey etc.;² in the Thanet Beds (Eocene) of the N.E. London Basin.³

Possible Sources of Derivation. Of secondary origin, derived by oxidation of manganese present in various rocks; metalliferous veins; organic.

REMARKS.—Pyrolusite occurs chiefly as an authigenic constituent of detrital sediments, also frequently as dendritic aggregates on the joint planes of sediments and on individual pebbles. Should always be confirmed by chemical test: borax bead attains a violet-red colour in oxidising flame; fused with Na_2CO_3 yields a bluish-green mass.

References.

¹ H. B. Milner, *Proc. Geol. Assoc.*, 36, 1925, p. 312.

² G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915-16, p. 89.

³ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 71, 1915, p. 577.

PYROPE

(GARNET GROUP)

Chem. Comp. $3\text{MgO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{SiO}_2$.

System. Isometric.

Habit. Dodecahedral (110), trapezohedral (211) etc., but rarely crystallised.

Structure. Fragmentary.

Cleavage. None.

Fracture. Conchoidal.

Hardness. 7.

Spec. Grav. 3.51.

Lustre. Vitreous.

Colour. Red, crimson, purplish-red. Translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. high, $n = 1.705$. Optically isotropic: seldom anomalous in this respect.

Characters in Sediments. Pyrope occurs as either rolled or shapeless, angular grains of deep red or purple-red colour. Tendency to alteration to a green decomposition product known as "kelyphite," an intimate intergrowth of fibrous amphibole and feldspar; also exhibits alteration to chlorite minerals.

Occurrence. In the Red Crag Ironstone of Netley Heath, Surrey;¹ in the Black Sands of Idaho, U.S.A.;² in alluvium and gravels of Arizona and Utah, U.S.A.³

Possible Sources of Derivation. Ultrabasic igneous rocks; almost exclusively confined to serpentine and peridotite,

REMARKS.—A well-known source of pyrope is the famous "blue ground" (serpentine breccia), diamondiferous deposits of Kimberley, South Africa.

References.

- ¹ P. G. H. Boswell, in H. G. Dines and F. H. Edmunds, "The Geology of the Country around Aldershot and Guildford." *Mem. Geol. Surv., Great Britain*, 1929, p. 114.
- ² E. V. Shannon, *Proc. U.S. National Mus.*, 60, 1921, p. 1.
- ³ H. E. Gregory, *Econ. Geol.*, 11, 1916, p. 223.

PYROPHYLLITE

(KAOLINITE GROUP)

Chem. Comp. $\text{Al}_2\text{O}_3 \cdot 4\text{SiO}_2 \cdot \text{H}_2\text{O}$.

System. Orthorhombic? (Pseudo-hexagonal).

Habit. Tabular, lamellar || (001), bladed, fibrous.

Structure. Crystalline.

Cleavage. Perfect || (001).

Fracture. Uneven.

Hardness. 1-1.5.

Spec. Grav. 2.6-2.9.

Lustre. Vitreous, pearly.

Colour. Colourless, white, grey, pale green. Transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low, $\alpha = 1.552$, $\beta = 1.588$, $\gamma = 1.600$. Birefringence strong, $\gamma - \alpha = 0.048$. Optically biaxial, negative. Optic axial plane \perp (001). $Bxa = X = c \perp$ (001). $Bxo = Z$ || elongation of bladed or fibrous grains. $2V = 57^\circ$. $2E = 98^\circ$. Dispersion weak, $\rho > v$.

Characters in Sediments. Diagnosed chiefly by its form, usually (001) flakes, or fibres and by its strong birefringence. It has a larger optic axial angle than muscovite with which it may be confused if uncoloured.

Occurrence. In certain soils of the United States.^{1, 2}

Possible Sources of Derivation. Metamorphic rocks, schist.

References.

- ¹ W. H. Fry, *Econ. Geol.* [Letter], 10, 1915, p. 292.
- ² W. J. McCaughey and W. H. Fry in W. O. Robinson, *U.S. Dept. Agric., Bull.* 122, 1914.

PYRRHOTITE

Chem. Comp. Fe_S , with impurities such as Cu, Ni and Co.

System. Hexagonal.

Habit. Tabular (basal), prismatic with pyramidal terminations. Sometimes twinned on (10 $\bar{1}$ 1).

Structure. Massive, less commonly crystalline.

Cleavage. Fair || (0001), poor || (11 $\bar{2}$ 0).

Fracture. Uneven, brittle.

Hardness. 3.5-4.5.

Spec. Grav. 4.53-4.77.

Lustre. Metallic.

Colour. Bronze-yellow, reddish-yellow, blackish-brown. Cream in vertical reflected light.

Mag Prop. Strongly magnetic (variable).

Elect. Prop. Good conductor.

Opt. Prop. Opaque. Rotates plane of polarised reflected light.

Characters in Sediments. This species, when present in detrital sediments is invariably irregular (ragged) in form and exhibits characteristic lustre in reflected light (as above). Rapidly alters to limonite, evinced by appearance of ochreous patches noted in many examples.

Occurrence. In the Upper Lias—Lower Inferior Oolite sands of the West of England;¹ in the Arctic Bed (Late Glacial) of the Lea Valley;² in the dune sands of South Wales (derived from the Pennant Grit and Llynfi rock, Swansea Bay).³

Possible Source of Derivation. Basic igneous rocks; metalliferous veins. In some cases authigenic.

REMARKS.—Relatively uncommon in detrital sediments, but when present it is apparent from the preliminary examination of the sample. It is readily dissolved in HCl and therefore does not appear in the cleaned "heavy" residue. Its magnetic properties, lustre, colour and lower specific gravity serve to distinguish it from pyrite, with which it may possibly be confused.

References.

¹ P. G. H. Boswell, *Geol. Mag.*, 61, 1924, p. 258.

² G. M. Davies, *Quart. Journ. Geol. Soc.*, 78, 1912, p. 247.

³ A. Stuart, *Proc. Geol. Assoc.*, 35, 1924, p. 323.

QUARTZ

[Pl. 5, facing p. 172, and Pl. 25, facing p. 332.]

Chem. Comp. SiO₂.

System. Trigonal.

Habit. Prismatic, with rhombohedral terminations, (10 $\bar{1}$ 1) and (0 $\bar{1}$ 11). Sometimes twinned about c or on (11 $\bar{2}$).

Structure Crystalline, cryptocrystalline, massive.

Cleavage. Rare || (10 $\bar{1}$ 1) and (0 $\bar{1}$ 11).

Fracture. Conchoidal.

Hardness. 7.

Spec. Grav. 2.66.

Lustre. Vitreous.

Colour. Colourless, purple, black, pink, yellow. Transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low, $\epsilon = 1.553$, $\omega = 1.544$. Birefringence weak, $\epsilon - \omega = 0.009$. Optically uniaxial, positive. Rarely biaxial with $2E = 12^\circ - 24^\circ$ (A. N. Winchell). Prismatic sections give straight extinction. Slow vibrations || length of crystal (ϵ).

Characters in Sediments. Variable in form and size, but usually in sub-angular, irregularly-shaped grains unless occurring in æolian deposits,

when roundness is marked. Very beautiful, doubly terminated euhedra occur in some sediments, often evidence of secondary crystallisation (external crystal faces in optical continuity with central nucleus). The common character of detrital quartz is that of the shapeless, slightly turbid grain with sharply defined inclusions: diagnosed by its low R.I. (almost the same as Canada balsam) and, in the majority of cases, by the "concentric ring" interference colours yielded by other than basal grains; the latter are isotropic and normally exhibit a positive interference figure. Inclusions are either fluid or mineral; the latter may be rutile, apatite, sillimanite, tourmaline, zircon or iron-ores, the former being gaseous or liquid, CO₂, water etc. Grains often exhibit undulose extinction due to strain.

Occurrence. Ubiquitous in detrital sediments. The following examples have been selected as covering practically all variations:—in the Torridonian Sandstone of Scotland;¹ in the Malvern Quartzite (Cambrian);² in the Old Red Sandstone of the Cardiff district;³ in the Carboniferous Limestone of Halkyn, N. Wales;⁴ in the Millstone Grit of Yorkshire;⁵ in the Keuper Marls of Charnwood, Leicestershire;⁶ in the Penrith Sandstone (Permian) of Penrith, Cumberland;⁷ in the Wealden Sands of Kent and Sussex;⁸ in the Lower Greensand etc., of Surrey;⁹ in the later Tertiary deposits of East England;¹⁰ in the dune sands of South Wales;¹¹ in Dartmoor detritals.¹²

Possible Sources of Derivation. Acid and intermediate rock types, more rarely basic. Sedimentary and crystalline metamorphic rocks. Metalliferous veins.

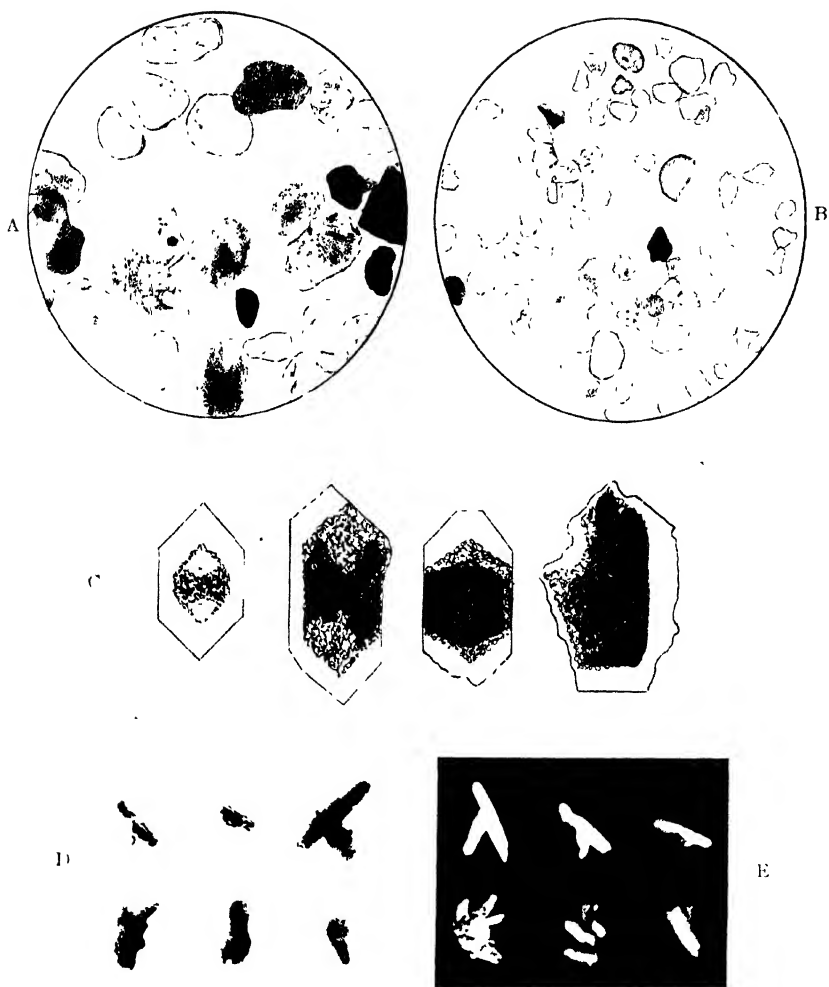
REMARKS.—Quartz is the most prolific constituent of detrital sediments, especially of the arenaceous and argillaceous types. Its detailed study in the "lighter" portion of the sediment is of great consequence, particularly when inclusions are present; these are, by their nature and abundance, frequently valuable indices of provenance.¹³

References.

- ¹ J. J. H. Teall, "Geology of the N.W. Highlands." *Mem. Geol. Surv. Scotland*, 1907, p. 284.
- ² G. S. Sweeting, *Proc. Geol. Assoc.*, 38, 1927, p. 550.
- ³ A. Heard and R. Davies, *Quart. Journ. Geol. Soc.*, 80, 1924, p. 497.
- ⁴ Author's observations (see Pl. 25).
- ⁵ A. Gilligan, *Quart. Journ. Geol. Soc.*, 75, 1919, p. 259.
- ⁶ T. O. Bosworth, "Keuper Marls around Charnwood." *Leicester Lit. and Phil. Soc.*, 1913, p. 89.
- ⁷ Well-known occurrence: see A. Harker, "Petrology for Students." (University Press, Cambridge), 1919, p. 206.
- ⁸ Author's observations, particularly the Tunbridge Wells Sand (Wealden) of Eridge etc., Sussex.
- ⁹ G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915-16, p. 87.
- ¹⁰ I. S. Double, *Proc. Geol. Assoc.*, 35, 1924, p. 335.
- ¹¹ A. Stuart, *Proc. Geol. Assoc.*, 35, 1924, p. 323.
- ¹² A. Brammall, *Proc. Geol. Assoc.*, 39, 1928, p. 46.
- ¹³ W. Mackie, *Trans. Edinburgh Geol. Soc.*, 7, 1897, p. 148. (Inclusions in quartz etc.)

General References.

- P. G. H. Boswell, "British Resources of Sands and Rocks used in Glass-making." 2nd ed. (Longmans Green, London), 1918 (for British quartzose sands of different stratigraphical ages, size and shape of grains, mechanical analyses etc.).
- C. Raeburn and H. B. Milner, "Alluvial Prospecting." (Murby, London), 1927, p. 416 (for alluvial quartz and varieties).



A-E. QUARTZ.

- A. Blown Sand, Newgate, Pembroke-shire. [x 25] (Note degree of rounding)
 B. Tunbridge Wells Sand, Eridge, Sussex. [x 15]
 C. Lihedra etc., extracted from Carboniferous Limestone, Halkyn, N. Wales
 [x 35]
 D. "Dogget" Sands, Md. Jurassic, Yorkshire. [x 38]
 E. "Dogget" Sands, Md. Jurassic, Yorkshire. *Polarised light*, [x 31]

RIEBECKITE

(AMPHIBOLE GROUP)

Chem. Comp. $\text{Na}_2\text{O} \cdot \text{Fe}_2\text{O}_3 \cdot \text{FeO} \cdot 5\text{SiO}_2 \cdot \text{H}_2\text{O}$.*System.* Monoclinic.*Habit.* Prismatic. Often vertically striated || c.*Structure.* Crystalline.*Cleavage.* Perfect || (110) at 124° .*Fracture.* Irregular.*Hardness.* 4.*Spec. Grav.* 3.44.*Lustre.* Vitreous, resinous.*Colour.* Dark blue to black. Translucent to opaque.*Mag. Prop.* Weakly magnetic.*Elect. Prop.* Weak conductor.

Opt. Prop. R.I. high, $\alpha = 1.697$, $\beta = 1.700$, $\gamma = 1.703$. Birefringence weak, $\gamma - \alpha = 0.006$. Optically biaxial, negative. Optic axial plane $\perp (010)$. $Bxa = X \wedge c = 0^\circ - 5^\circ$ in β . $Bxo = Z \perp (010)$. $X = b$. Optic axial angle large. Strong dispersion. Pleochroism strong: $X =$ indigo blue, green or green-blue $> Y =$ brown-yellow, violet or yellow $> Z =$ grey, yellow, black. Positive form known (fibrous variety *crocidolite*) in which $Z = b$, $Y \wedge c = 0^\circ \pm$. Also Y may $= b$ when $X \wedge c = 1^\circ - 8^\circ$.

Characters in Sediments. Riebeckite is a rare detrital mineral and often difficult to confirm optically owing to its deep colour. As in igneous rocks, it tends to occur (in sediments) in shapeless, ragged grains. Sometimes striations can be discerned which, together with colour, high R.I. and pleochroism, aid diagnosis. Differs from glaucophane (p. 289) in depth of colour and negative elongation.

Occurrence. In oil borings in Egypt;¹ in the Plateau Gravel, Sevenoaks, Kent;² in the sands of Tuscany, Italy.³

Possible Sources of Derivation. Soda-bearing igneous rocks (acid and intermediate types); metamorphic rocks.

References.

¹ T. W. Bowman, "Report on Boring for Oil in Egypt." *Section III, Eastern Desert and Adjoining Islands. Mines and Quarries Dept.*, Egypt, 1931.

² F. Chapman, *Geol. Mag.*, 1900, p. 404.

³ I. Chelussi, *Boll. Soc. geol. ital.*, 29, 1910, p. 207.

RUBY

(VARIETY OF CORUNDUM, q.v. p. 271)

RUTILE

[Pl. 26 A, B, facing p. 337.]

Chem. Comp. TiO_2 .*System.* Tetragonal.

Habit. Prismatic; acicular. Frequently striated || principal axis c, with transverse striæ || (101) due to polysynthetic twinning. Sometimes twinned about (101) either geniculate or as a network (sagenite).

Structure. Crystalline.*Cleavage.* Good || (110) and (100). Occasionally || (111).*Fracture.* Subconchoidal.*Hardness.* 6-6.5.

Spec. Grav. 4.18-4.25.

Lustre. Metallic, adamantine, vitreous.

Colour. Red, reddish-brown, yellow.

Mag. Prop. Non-magnetic.

Elect. Prop. Moderate conductor.

Opt. Prop. R.I. very high, $\epsilon=2.903$, $\omega=2.616$. Birefringence extreme, $\epsilon-\omega=0.287$. Optically uniaxial, positive. Straight extinction. Interference figure anomalous in twinned crystals, giving biaxial characters, "twinning bands crossing basal sections of the uniaxial mineral; in these bands the optic plane is $\parallel (110)$ " (A. N. Winchell). Length slow. Red and brown varieties usually pleochroic, weak: reddish-brown to brown or yellow. Maximum absorption direction \parallel principal axis.

Characters in Sediments. Two contrasted types of rutile are met with in sediments: well-formed prismatic grains with pyramidal terminations, often slightly rounded and anhedral fractured grains; the former are usually "foxy-red" or reddish-brown in colour, the latter being commonly of an amber tint. The degree of rounding of grains is a variable factor, often being slight compared with associated minerals. Long, slender "needles" of a red-brown to almost black colour are highly characteristic of many metamorphosed, argillaceous rocks, e.g. phyllites, slates etc. In addition, geniculate twins are found in certain sands, especially in alluvials, the two individuals making an angle of about 65° with one another. Many prismatic grains exhibit characteristic striations running obliquely to the prism-edge, due to polysynthetic twinning $\parallel (101)$. Inclusions of iron-ore rare. Diagnosed chiefly by tetragonal (prismatic) form and cleavage, brilliant metallic to vitreous lustre, colour, high R.I. and diagonal striae when developed.

Occurrence. Extremely common in detrital sediments from all geological horizons. The following occurrences and records cover practically all types noted:—in the Bunter Pebble Beds of the West of England;¹ in the Upper Lias—Lower Inferior Oolite sands of the West of England;² in the Northampton Ironstone;³ in the Upper Tunbridge Wells Sands (Wealden), Tunbridge Wells, Kent;⁴ in the Lower Greensand of N.W. Wiltshire⁵ and Cambridgeshire⁶ etc.; in all Lower Tertiary sands of the Hampshire and London basins;⁷ in the Pliocene sands of Cornwall;⁸ in the later Tertiary deposits of East England;⁹ in the dune sands of South Wales;¹⁰ in Dartmoor detritals.¹¹

Possible Sources of Derivation. Acid igneous rocks, crystalline metamorphic rocks. Frequently derived *in situ* from the decomposition of ilmenite.

REMARKS.—Sagenite, the "lattice" form of rutile, composed of a number of individuals involved in geniculate twinning, is an infrequent occurrence in detrital sediments. When present it probably owes its preservation to a host such as biotite or a member of the chlorite group from which it is released by their decomposition.

References.

¹ H. H. Thomas, *Quart. Journ. Geol. Soc.*, 58, 1902, p. 622.

² P. G. H. Boswell, *Geol. Mag.*, 61, 1924, p. 253.

³ J. G. A. Skerl, *Proc. Geol. Assoc.*, 38, 1927, p. 380.

⁴ H. B. Milner, *Proc. Geol. Assoc.*, 34, 1923, p. 49 and Pl. 5.

⁵ Author's observations.

⁶ R. H. Rastall, *Geol. Mag.*, 1919, p. 219.

⁷ General observations; see particularly P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 71, 1915, p. 576, 581 and table iv. (for N.E. London basin);

- S. W. Wooldridge, *Proc. Geol. Assoc.*, 35, 1924, p. 379 (for Bagshot Beds of Essex).
- ⁸ H. B. Milner, *Quart. Journ. Geol. Soc.*, 78, 1922, p. 359, 361.
- ⁹ I. S. Double, *Proc. Geol. Assoc.*, 35, 1924, p. 338.
- ¹⁰ A. Stuart, *Proc. Geol. Assoc.*, 35, 1924, p. 322.
- ¹¹ A. Brammall, *Proc. Geol. Assoc.*, 39, 1928, p. 34; also A. Brammall and H. F. Harwood, *Mineral. Mag.*, 22, 1923, p. 20.

General References.

- C. Raeburn and H. B. Milner, "Alluvial Prospecting." (Murby, London), 1927, p. 422 (for alluvial rutile, sagenite etc.).
- P. G. H. Boswell, "Some Rare Detrital Minerals in British Sedimentary Rocks." *Trans. Geol. Soc., Glasgow*, 18, 1927, p. 129.
- A. B. Dick, "On Needles of Rutile in the Test of *Bathysiphon argenteus*." *Trans. Edinburgh Geol. Soc.*, 12, 1928, p. 19.

SANIDINE

(VARIETY OF ORTHOCLASE FELSPAR, *q.v.* p. 321)

SAPPHIRE

(VARIETY OF CORUNDUM, *q.v.* p. 271)

SELENITE

See Gypsum, p. 293.

SERPENTINE

Hitherto the record of "serpentine" in sediments has implied either fragmentary serpentine rock or the minerals "antigorite" (p. 242) or "chrysotile" (p. 267). Antigorite is now classed as an end-member of the chlorite group (p. 264), wherein it undoubtedly possesses close affinities with other species so designated. Chrysotile is a distinctive species, but apparently dimorphous with antigorite; it is therefore treated separately in this book and the term "serpentine" as a mineral is dropped. References to occurrences of "serpentine" are, however, given here for convenience:—

In the Devonian and Culm sediments of the Torquay district;¹ in the Permian Rocks of the Torquay promontory;² in the new Red Sandstone of the West of England;³ in the sands of the Upper Lias-Lower Inferior Oolite of the West of England;⁴ in the shore sands in proximity to the serpentine masses of the Lizard district, Cornwall;⁵ in recent deposits of Pavia etc., Northern Italy;⁶ in deposits of doubtful age (? Eocene) of Marazion, Cornwall.⁷

References.

- ¹ W. G. Shannon, *Proc. Geol. Assoc.*, 39, 1928, p. 139, 142.
- ² W. G. Shannon, *Proc. Geol. Assoc.*, 38, 1927, p. 134.
- ³ H. H. Thomas, *Quart. Journ. Geol. Soc.*, 65, 1909, p. 239.
- ⁴ P. G. H. Boswell, *Geol. Mag.*, 61, 1924, p. 252.
- ⁵ Author's observations.
- ⁶ E. Tacconi, *Rend. R. Ist. lombardo*, ser. 2, 34, 1901, p. 873.
- ⁷ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 79, 1923, p. 213, 226.

SIDERITE (Chalybite)

[Pl. 26 c, facing p. 337.]

Chem. Comp. FeCO_3 .*System.* Trigonal.*Habit.* Simple rhombohedron, often with curved faces. Spherulitic.*Structure.* Crystalline, massive, compact, radiating in spherulites.*Cleavage.* Perfect rhombohedral $\parallel (10\bar{1}1)$.*Fracture.* Uneven. Brittle.*Hardness.* 3.5-4.*Spec. Grav.* 3.78-3.89.*Lustre.* Vitreous, dull.*Colour.* Shades of brown or grey. Translucent to opaque.*Mag. Prop.* Non-magnetic.*Elect. Prop.* Non-conductor.

Opt. Prop. R.I. very high, $\omega = 1.875$, $\epsilon = 1.633$. Birefringence extreme, $\omega - \epsilon = 0.242$. Optically uniaxial, negative. In translucent grains, "twinkling," due to different R.I. values, noted on rotation of polariser alone. Radiating masses exhibit brush-polarisation (or "black cross") effects. Often possesses distinct absorption.

Characters in Sediments. Subangular or rounded rhombohedral grains determined principally by cleavage. Also as spherulitic or slightly ellipsoidal grains of characteristic form, colour and traces of radiate structure on fractured edges. Diagnosed chiefly by form, yellow-brown colour, both R.I. values *higher* than Canada balsam (unlike calcite (p. 257), dolomite (p. 278), magnesite (p. 309) and absorption.

Occurrence. In the Devonian rocks of the Torquay district;¹ in the Millstone Grit, Snail Green, near Bradford;² in the Upper Coal Measures of South Wales;³ in the Etruria Marls and Blackband Group (Upper Coal Measures) of Staffordshire;⁴ in the Coal Measure Sediments of Durham;⁵ in the Marlstone Ironstone (Middle Lias) of Leicestershire;⁶ in the Fairlight Clays (Wealden) of Fairlight, Sussex;⁷ in St. Ives Bay sand, Cornwall.⁸

Possible Sources of Derivation. Clay ironstone and allied stratified deposits, also from metalliferous veins.

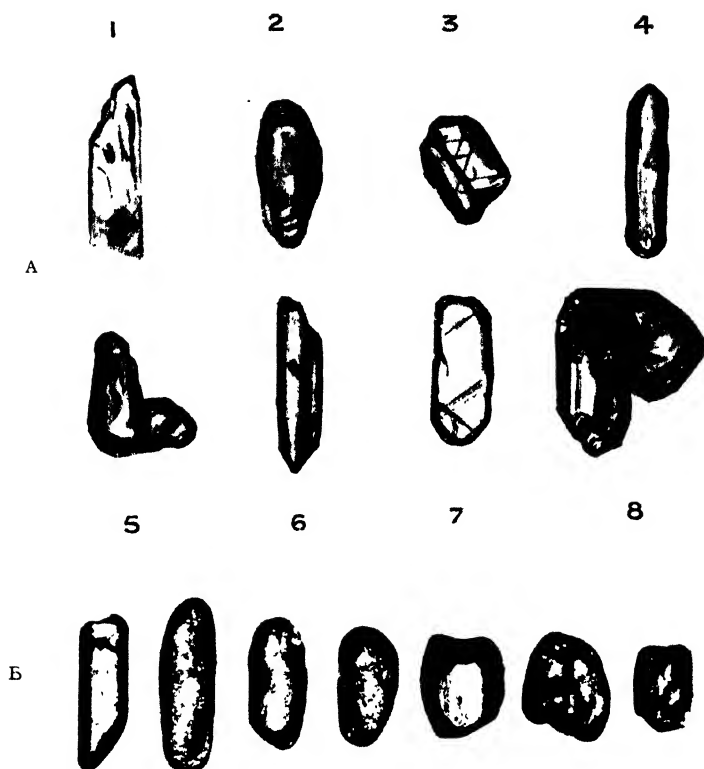
REMARKS.—By no means a common mineral in detrital sediments, only occurring locally under suitable conditions. Siderite is insoluble in cold dilute HCl (unlike calcite (p. 258) and dolomite (p. 278)).

*References.*¹ W. G. Shannon, *Proc. Geol. Assoc.*, 39, 1928, p. 142.² J. A. Butterfield, *Trans. Leeds Geol. Assoc.*, 5, 1933, p. 97.³ E. Spencer, *Quart. Journ. Geol. Soc.*, 81, 1925, p. 675.⁴ J. G. Kellett, *Proc. Univ. Durham Phil. Soc.*, 7, 1926, p. 208.⁵ W. A. Richardson, *Trans. Inst. Min. Eng.*, 60, 1921, p. 337.⁶ H. B. Milner, *Proc. Geol. Assoc.*, 36, 1925, p. 315; also E. Spencer, *op. cit. sup.*, p. 670.⁷ T. Crook and G. M. Davies, *Geol. Mag.*, 1909, p. 122.*General Reference.*

E. Spencer, "On Occurrences of Spherulitic Siderite etc., in Sediments." *op. cit.*, p. 232.

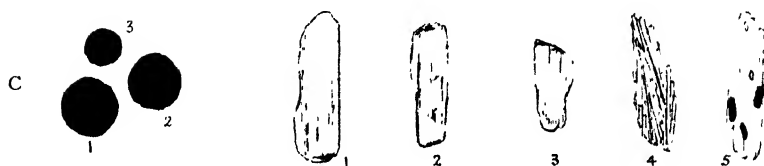
SILLIMANITE [Pl. 26 d, facing p. 337.]*Chem. Comp.* $\text{Al}_2\text{O}_3 \cdot \text{SiO}_2$.*System.* Orthorhombic.

Habit. Prismatic, rectangular, with irregular terminations, fibrous. Sometimes vertically striated $\parallel c$.



A, B. RUTILITE.

- A 1, 6, 7 Lower Greensand, N.W. Wiltshire [X 70]
 A 2-4 Timbridge Wells Sand, Kent [X 60]
 A 5 Gemiculate twin, Timbridge Wells Sand, Kent [X 100]
 A 8 Gemiculate twin, Recent Sands, Ceylon [X 70]
 B Tertiary, New South Wales [X 57]



C. SPHERULITIC SIDERITE.

- C 1-3 Fairlight Clay, Fairlight Glen, Hastings, Sussex [X 45]

D. SILLIMANITE.

- D 1-4 Phocenc Sand, Bentley, Suffolk. [1-3, X 45 | 4, X 60.]
 D 5 Recent Sand, Dinard, Brittany. [X 45]

Structure. Crystalline.

Cleavage. Good \parallel (010).

Fracture. Irregular.

Hardness. 6-7.5.

Spec. Grav. 3.23-3.25.

Lustre. Vitreous.

Colour. Usually colourless, yellow, pale shades of brown, green or grey. Transparent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. high, $\alpha = 1.659$, $\beta = 1.660$, $\gamma = 1.680$. Birefringence moderate, $\gamma - \alpha = 0.021$. Optically biaxial, positive. Optic axial plane \parallel (010). Straight extinction \parallel prism edge. Compensates \perp to length. $Bxa = Z \perp (001)$, i.e. $\parallel c$. $X = b$. $2V = 20^\circ$. $2E = 33^\circ$. Occasionally pleochroic, especially if much coloured: X = pale brown or yellow, Y = brown or green, Z = dark brown or blue. Strong dispersion, $\rho > v$.

Characters in Sediments. Usually found as slender prisms or fibres, sometimes flattened, with fractured or irregular terminations. Tendency to display traces of longitudinal "splitting." Flattened grains \parallel (001) exhibit good biaxial figure and low birefringence due to $\beta - \alpha = 0.001$. Grains with regular striations are comparatively rare; curved forms are occasionally met with. Inclusions of spinel, biotite or glass (A. N. Winchell).

Occurrence. In the Bunter Pebble Beds of the West of England;¹ in the New Red Sandstone of the West of England;² in the Lower Greensand of Limpsfield, Surrey;³ in the Lenham Beds, Sanderstead, Surrey;⁴ in the Red Crag, Bentley, Suffolk;⁵ in the Northampton Ironstone;⁶ in the Lower Greensand of the Dorking-Leith Hill district, Surrey;⁷ in the Lower Eocene deposits of the North-Eastern part of the London Basin;⁸ in the later Tertiary deposits (Red Crag, Norwich Crag, Chillesford Beds, Forest Bed and *Leda myalis* Bed) of East England;⁹ in deposits of doubtful age, Marazion, Cornwall;¹⁰ in the Dartmoor detritals.¹¹ "Its occurrences in the Bunter, Upper Lias, Inferior Oolite, Callovian, Thanet Beds, Reading Beds, Claygate Beds, Bagshot Beds, Upper Headon Beds, and the Pliocene of East Anglia and Cornwall, as well as more recent deposits in Scotland, Ireland and England, are sporadic and rare."¹²

Possible Sources of Derivation. Crystalline metamorphic rocks.

REMARKS.—Sillimanite is essentially a local species in Britain. It is distinguished from topaz and andalusite by its higher birefringence and smaller axial angle, andalusite having negative, sillimanite positive elongation; from kyanite, which at first sight it often resembles, by straight extinction, high interference colours and lower R.I.

References.

- ¹ H. H. Thomas, *Quart. Journ. Geol. Soc.*, 58, 1902, p. 621.
- ² H. H. Thomas, *Quart. Journ. Geol. Soc.*, 65, 1909, p. 231.
- ³ G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915-16, p. 91.
- ⁴ F. Gossling and S. W. Wooldridge, *Proc. Geol. Assoc.*, 37, 1926, p. 99.
- ⁵ Author's observations.
- ⁶ J. G. A. Skerl, *Proc. Geol. Assoc.*, 38, 1927, p. 375.
- ⁷ H. A. Hayward, *Proc. Geol. Assoc.*, 43, 1932, p. 1.
- ⁸ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 72, 1916, p. 536.
- ⁹ I. S. Double, *Proc. Geol. Assoc.*, 35, 1924, p. 340.
- ¹⁰ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 79, 1923, p. 226.
- ¹¹ A. Brammall, *Proc. Geol. Assoc.*, 39, 1928, p. 47.
- ¹² P. G. H. Boswell, "The Rarer Detrital Minerals of British Sedimentary Rocks." *Trans. Geol. Soc. Glasgow*, 18, 1926-27, p. 140.

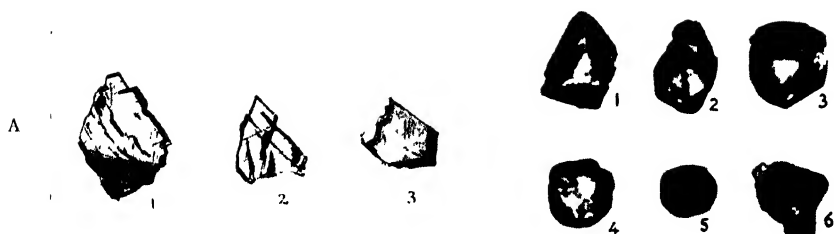
SPESSARTITE

(GARNET GROUP)

Chem. Comp. $3(\text{Mn, Fe, Ca})\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{SiO}_2$.*System.* Isometric.*Habit.* Dodecahedral, trapezohedral.*Structure.* Crystalline, granular.*Cleavage.* None.*Fracture.* Uneven.*Hardness.* 7.*Spec. Grav.* 3.8-4.25.*Lustre.* Vitreous.*Colour.* Salmon pink, yellow, brown, transparent to translucent.*Mag. Prop.* Weakly magnetic.*Elect. Prop.* Poor conductor*Opt. Prop.* R.I. very high, $n=1.805$. Optically isotropic. Some specimens show distinct anisotropism, probably due to strain.*Characters in Sediments.* Spessartite is a rare detrital mineral but is to be identified by its colour, very high R.I. and tendency to show superficial alteration to biotite.*Possible Sources of Derivation.* Acid igneous rocks, e.g. granite, rhyolite; also low-grade metamorphosed sediments.**SPHALERITE (Zinc Blende)**

[Pl. 27 A, B, facing p. 338.]

Chem. Comp. ZnS . Sometimes with Fe.*System.* Isometric.*Habit.* Tetrahedral, dodecahedral or combination of cube and dodecahedron. Frequently twinned: twin lamellæ || tetrahedron faces.*Structure.* Crystalline, massive, granular.*Cleavage.* Perfect || (110).*Fracture.* Conchoidal.*Hardness.* 3.5-4.*Spec. Grav.* 4-4.1.*Lustre.* Adamantine, metallic, resinous. Grey in vertical reflected light.*Colour.* Black, brown, yellow; sometimes green. Opaque, sometimes translucent.*Mag. Prop.* Weakly magnetic to moderately magnetic when Fe is present.*Elect. Prop.* Good conductor.*Opt. Prop.* R.I. very high (in translucent crystals), $n=2.37$. Increases with Fe content. Isotropic. Sometimes anisotropic due to strain.*Characters in Sediments.* This mineral may either occur in quite opaque tetrahedral or dodecahedral grains or in translucent brown granules of high refractive index and obvious isotropism. If in the opaque form, the striations || the tetrahedral faces are usually developed and are very characteristic. Its resinous lustre and indication of a perfect dodecahedral cleavage are further properties to be looked for. In some sediments, e.g. clays, sphalerite occurs in significant spherical shapes with or without radiating structure suggestive of replacement of organic bodies. The translucent coloured grains (colouring may be zonal) are extremely difficult to differentiate from other similarly coloured detrital minerals and chemical tests on bulk material (if possible) are desirable. Distinguished from rutile, brookite, cassiterite and titanite by the anisotropism of those



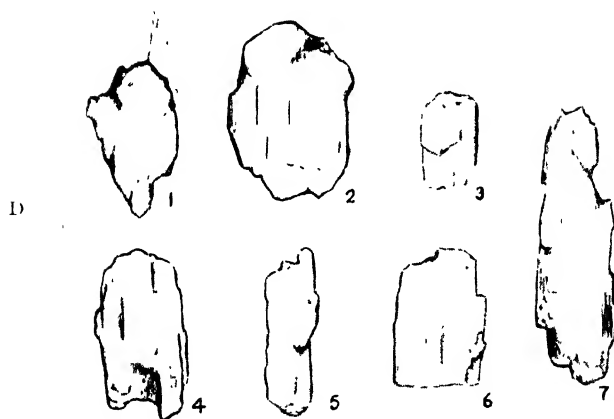
A. B. SPHALERITE.

- A 1-3 Middle Tias Ironstone, Cleveland, Yorkshire [x 40]
 B 1-3 "Dogger" Ironstone, Md. Jurassic, Yorkshire [x 116]
 B 4-6 Fuller's Earth (Aptian), Surrey [x 8];



C SPINEL.

Alluvials, Ceylon [x 59]



D. SPODUMENE.

- D. 1-6 Recent Sand, Carrickmores, Ireland. [x 60]
 D. 7 Annamoe River, Ireland. [x 80.]
 (From brush-drawings by F. Smithson)

species; but may be confused with brown garnet, chromite or picotite if in small grains.

Occurrence. In the Middle Lias (Cleveland Ironstone) of Yorkshire;¹ in the Jurassic Fuller's earth of Combe Hay, Bath, Somerset;² in the Fuller's earth (Aptian) of Redhill, Surrey;³ also at Nutfield, Surrey;⁴ in the shore sand of Lelant, Cornwall.⁵

Possible Sources of Derivation. From veins and irregular ore bodies in limestones; from metalliferous veins associated with galena, pyrite, copper ores etc. In Fuller's earth, clays etc., may be formed as a result of organic decomposition.

REMARKS.—In a personal communication to the author, G. M. Davies draws attention to the commonly noted association of sphalerite and Fuller's earth, not only in Aptian deposits, but also in the Jurassic Fuller's earth, e.g. Combe Hay, near Bath.

References.

- ¹ J. E. Stead, *Proc. Cleveland Inst. Eng.*, 1910, p. 75; also A. F. Hallimond, *Mem. Geol. Sur., Min. Res. Gt. Brit.*, 29, "Iron Ores." 1925, p. 52.
- ² E. F. Newton, *Proc. Geol. Assoc.*, 48, 1937, p. 188.
- ³ G. M. Davies, *Proc. and Trans. Croydon Nat. Hist. Soc.*, 1915-16, p. 86.
- ⁴ E. F. Newton, *op. cit.*, p. 179.
- ⁵ Author's observation.

General Reference.

H. H. Thomas and D. A. MacAlister, "The Geology of Ore Deposits." (Arnold, London), 1909.

SPHENE

See Titanite, p. 345.

SPINEL

[Pl. 27 c, facing p. 338.]

(SPINEL GROUP)

Chem. Comp. $MgO \cdot Al_2O_3$.

System. Isometric.

Habit. Octahedral.

Structure. Crystalline.

Cleavage. Poor || (111).

Fracture. Conchoidal.

Hardness. 8.

Spec. Grav. 3.6.

Lustre. Vitreous.

Colour. Shades of red, reddish-yellow, blue, green.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. high, $n = 1.718$.

Characters in Sediments. Generally occurs as well rounded octahedral grains, much "pitted" from uneven abrasion. The conchoidal fracture, if developed, is very characteristic. Recognised by its high R.I., colour and isotropism.

Occurrence. In Keuper rocks at Wimslow, Cheshire;¹ in the Upper Kimmeridge Clay and Portland Sand of Dorset, Wiltshire, Oxfordshire and Buckinghamshire;² in the Jurassic "Sands" from the North Cotteswolds;³ in the Carstone and Red Chalk of Yorkshire and Lincolnshire;⁴ in the Ashdown Sand of Etchingam and Robertsbridge, Sussex;⁵ in the Folkestone Beds of the Dorking-Leith Hill district, Surrey;⁶ in the Lenham Beds, Sanderstead, Surrey;⁷ in the Thanet Beds of Suffolk and Essex;⁸ in the dune sands of South Wales;⁹ in the Dartmoor detritals;¹⁰ in St. Ives Bay sand, Cornwall;¹¹ in beach sands between St. John's river and St. Augustine, Florida, U.S.A.;¹² beach sands between Charleston, South Carolina and Miami, Florida, U.S.A.¹³

Possible Sources of Derivation. Metamorphosed limestone, crystalline schist, dolomitic limestone.

REMARKS.—Common red spinel seems to be extremely rare in detrital sediments, though its resemblance to almandine garnet may have caused it to be overlooked in some instances. It differs from garnet in its lower S.G., non-magnetic properties and usual octahedral habit, but positive diagnosis by the microscope alone is certainly difficult. Appeal to R.I. test by immersion in methylene iodide is suggestive: spinel is nearly always less than, garnet, greater than that liquid (1.737) [A. Brammall]. Other members of the spinel group recorded from sediments are described, ceylonite (p. 260), chromite (p. 266), hercynite (p. 296), magnetite (p. 310), picotite (p. 325).

References.

- ¹ S. W. Alty, *Proc. Liverpool Geol. Soc.*, 14, 1926, p. 278.
- ² E. Neaverson, *Proc. Geol. Assoc.*, 36, 1925, p. 240.
- ³ J. G. A. Skerl, *Proc. Cotteswold Nat. Field Club*, 23, 1925, p. 153.
- ⁴ H. C. Versey and C. Carter, *Proc. Yorks. Geol. Soc.*, 20, 1926, p. 349.
- ⁵ A. A. Fitch, *Proc. Geol. Assoc.*, 41, 1930, p. 53.
- ⁶ H. A. Hayward, *Proc. Geol. Assoc.*, 43, 1932, p. 1.
- ⁷ F. Gossling and S. W. Wooldridge, *Proc. Geol. Assoc.*, 37, 1926, p. 92.
- ⁸ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 71, 1916, p. 536.
- ⁹ A. Stuart, *Proc. Geol. Assoc.*, 35, 1924, p. 321.
- ¹⁰ A. Brammall, *Proc. Geol. Assoc.*, 39, 1928, p. 47.
- ¹¹ T. Crook and G. M. Davies, *Geol. Mag.*, 1909, p. 122.
- ¹² J. H. C. Martens, 19th Ann. Rep. Florida State Geol. Surv., 1928, p. 130.
- ¹³ J. H. C. Martens, *Bull. Geol. Soc. Amer.*, 46, 1935, p. 1580.

SPODUMENE (Triphane)

(PYROXENE GROUP)

[Pl. 27 D, facing p. 338.]

Chem. Comp. $\text{Li}_2\text{O} \cdot \text{Al}_2\text{O}_3 \cdot 4\text{SiO}_2$.

System. Monoclinic.

Habit. Prismatic, often flattened || (100). Also twinned about (100). Frequently exhibits vertical striae.

Structure. Crystalline, massive, cleavable. Lamellar || (100) due to twinning.

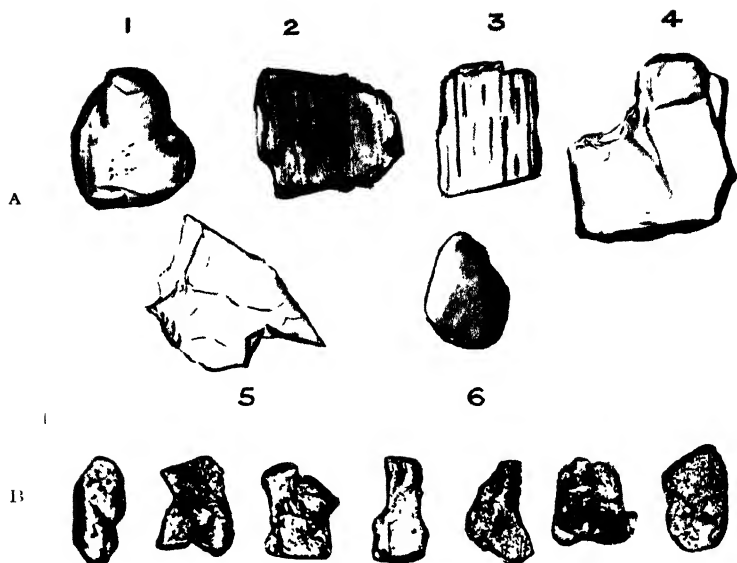
Cleavage. Perfect || (110), parting || (010), rarely (100).

Fracture. Subconchoidal, irregular.

Hardness. 6.5-7.

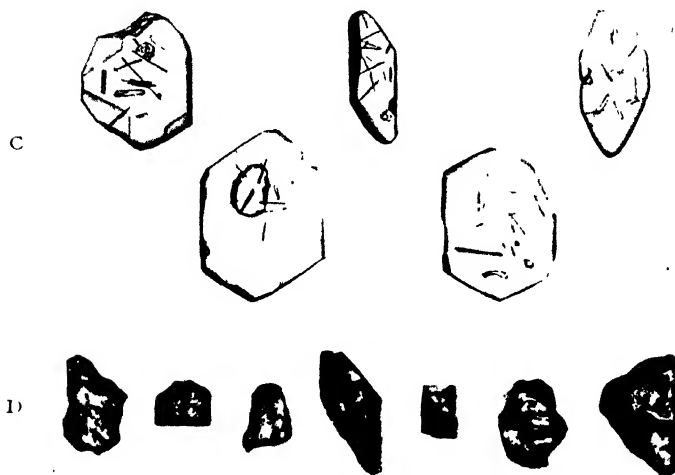
Spec. Grav. 3.1-3.2.

Lustre. Vitreous, pearly on (110).



A, B STAUROLITE.

- A 1. Pliocene Sands, St. Erth, Cornwall. [x 70.]
 A 2. Lower Greensand, N. W. Wiltshire. [x 70.]
 A 3-5. Alluvials, W. Africa. [x 70.]
 A 6. Blown Sand, Newgate, Pembroke-shire. [x 70.]
 B. Lower Greensand, Isle of Wight. [x 50.]



C, D. TITANITE

- C. Fuller's Earth, Nutfield. [x 200.] (From brush-drawing by E. F. Newton.)
 D. Shore Sand, Galway. [x 57.]

Colour. Green, greenish-white, mauve, yellow, pink. Transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. high, $\alpha = 1.660$, $\beta = 1.666$, $\gamma = 1.676$. Birefringence moderate, $\gamma - \alpha = 0.016$. Optically biaxial, positive. Optic axial plane $\parallel (010)$. $Bxa = Z$ inclined at $23^\circ - 27^\circ$ to c in the obtuse angle β . $Y = b$. Oblique extinction, angle 26° or less. $2V = 54^\circ - 60^\circ$. Dispersion weak, $\rho < \nu$. Coloured varieties exhibit weak pleochroism: $X = \text{purple} > Y = \text{pink or mauve} > Z = \text{colourless (kunzite) or } X = \text{green} > Y = \text{green} > Z = \text{colourless (hiddenite)}$.

Characters in Sediments. Occurs rarely, either as fairly perfect euhedral crystals not unlike titanite in habit, or in the form of irregular and much fractured prismatic grains of distinctive pale green, greenish-mauve or pink colour; the former approximate the variety hiddenite, the latter (pink to lilac) kunzite. Characterised by prismatic cleavage, often traces of parting $\parallel (010)$, oblique extinction angle up to 26° and sometimes by the presence of a fibrous alteration product (cymatolite). Indeterminate inclusions observed.

Occurrence. In Pliocene-Pleistocene and Recent sands of Southern California;¹ in rocks of similar age in the Lazard area, San Joaquin Valley, California;² in sands and soils derived from granite, Carrickmines Golf Course, Dublin district.³

Possible Sources of Derivation. Granite, granite pegmatite, gneiss, mica-schist.

REMARKS.—The records of this mineral occurring in detrital sediments are very scanty and it has probably been overlooked in certain cases of pyroxene-rich sediments where, from the nature of the contributing parent-rocks, it might have been expected to occur. Its optical properties are sufficiently distinctive for diagnosis, coupled with the characteristic habit, cleavage and colour. It readily yields a red flame with the blowpipe (Li_2O).

References.

¹ Author's observations.

² R. D. Reed and J. P. Bailey, *Bull. Amer. Assoc. Petrol. Geol.*, 11, 1927, p. 363.

³ F. Smithson, *Geol. Mag.*, 65, 1928, p. 24 and Fig. 2 (11, 12).

General Reference.

C. Raeburn and H. B. Milner, "Alluvial Prospecting." (Murby, London), 1927, p. 430 (for alluvial spodumene, kunzite etc.).

STAUROLITE

[Pl. 28 A, B, facing p. 341.]

Chem. Comp. $2\text{FeO} \cdot 5\text{Al}_2\text{O}_3 \cdot 4\text{SiO}_2 \cdot \text{H}_2\text{O}$.

System. Orthorhombic.

Habit. Prismatic; sometimes twinned about (032) cruciform, or on (232) giving cross at $60^\circ 31'$.

Structure. Crystalline.

Cleavage. Good $\parallel (010)$, rarely $\parallel (110)$.

Fracture. Subconchoidal, "hackly."

Hardness. 7-7.5.

Spec. Grav. 3.65-3.77.

Lustre. Vitreous.

Colour. Reddish-brown, brown, brownish-yellow, straw-yellow. Transparent to translucent.

Mag. Prop. Weakly magnetic.

Elect. Prop. Bad conductor.

Opt. Prop. R.I. high, $\alpha=1.736$, $\beta=1.741$, $\gamma=1.746$. Birefringence moderate, $\gamma-\alpha=0.010$. Optically biaxial, positive. Optic axial plane $\parallel (100)$. $Bxa=Z \parallel c \perp (001)$. $X \parallel b$, $Y \parallel a$. $2V=88^\circ \pm$. Prismatic sections show straight extinction. Pleochroism moderate: $X=\text{colourless}$ $< Y=\text{pale yellow}$ $< Z=\text{golden yellow}$. Dispersion weak, $\rho > \nu$.

Characters in Sediments. Well crystallised grains are comparatively rare, the usual type being irregular or somewhat platy grains determined largely by cleavage, having marked "hackly" fracture and haphazard boundaries. In a few cases, very perfect euhedra are seen, generally of a delicate lemon-yellow tint and exhibiting the characteristic pleochroism. Grains with "concertina" boundaries (due probably to solution) are sometimes met with. Intensity of pleochroism varies greatly. Inclusions are common, especially quartz; garnet, tourmaline, rutile, biotite and carbonaceous matter have all been observed; such inclusions are usually commoner in the deeper coloured varieties. H. H. Thomas has described some well formed crystals from the New Red Sandstone of the West of England, which are tabular $\parallel (010)$, modified by (110) and terminated by forms (101) and (001) ; such grains constitute a rare type in sediments generally. A still rarer type in detrital sediments is that of the cruciform twin, the two individuals being disposed at right angles. Superficial decomposition to a member of the chlorite group or to green mica may be noted in some instances.

Occurrence. A widespread mineral in British strata; the following selection indicates the range of this mineral and exemplifies all varieties:—Upper Llandovery (Silurian), in the Halesowen Sandstone (Upper Carboniferous), in the Keele Beds (Upper Carboniferous), the Enville and Permian rocks, Bunter and Keuper Sandstones etc., of the English Midlands;¹ in the Old Red Sandstone (Downtonian) of the West Midlands;² in the Bunter Pebble Bed of the West of England;³ in the Keuper Marls around Charnwood, Leicestershire;⁴ in the New Red Sandstone of the West of England;⁵ in the Permian Yellow Sands of Yorkshire;⁶ in the Upper Lias—Lower Inferior Oolite of the West of England;⁷ in the Northampton Ironstone;⁸ in the Portland Sand of Dorset;⁹ in the Tunbridge Wells Sand (Wealden) of Kent etc.;¹⁰ in the Lower Greensand of Surrey;¹¹ in the Carstone of Yorkshire and Lincolnshire;¹² in the Cretaceous and Eocene of Haldon Hills, in the Oligocene of Bovey and Petrockstow, Devonshire;¹³ in the Bagshot Beds (Eocene) of Essex;¹⁴ in the Pliocene of West Cornwall;¹⁵ in the later Tertiary deposits of East England;¹⁶ in surface deposits of S.E. Devonshire.¹⁷

Possible Sources of Derivation. Crystalline schists, contact metamorphic rocks.

REMARKS.—Staurolite often occurs in association with garnet, kyanite and sillimanite in metamorphic rocks, this association being common in many sediments thence derived. Very beautiful alluvial staurolite comes from the Gold Coast, Nigeria etc. (West Africa). See *General Reference* below.

References.

¹ W. F. Fleet, *Geol. Mag.*, 62, 1925, p. 98.

² W. F. Fleet, *Geol. Mag.*, 63, 1926, p. 513.

³ H. H. Thomas, *Quart. Journ. Geol. Soc.*, 58, 1902, p. 625 and *Pl.* 32, *Fig.* 7.

- ⁴ T. O. Bosworth, *Quart. Journ. Geol. Soc.*, 68, 1912, p. 289.
- ⁵ H. H. Thomas, *Quart. Journ. Geol. Soc.*, 65, 1909, p. 234, and *Pl.* 12, *Figs.* 4a, 4b, 4c.
- ⁶ H. C. Versey, *Proc. Yorks. Geol. Soc.*, 20, 1925, p. 207.
- ⁷ P. G. H. Boswell, *Geol. Mag.*, 61, 1924, p. 254.
- ⁸ J. G. A. Skerl, *Proc. Geol. Assoc.*, 38, 1927, p. 382.
- ⁹ M. P. Latter, *Proc. Geol. Assoc.*, 37, 1926, p. 83.
- ¹⁰ H. B. Milner, *Proc. Geol. Assoc.*, 34, 1923, p. 49.
- ¹¹ G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915-16, p. 84, 92.
- ¹² H. C. Versey and C. Carter, *Proc. Yorks. Geol. Soc.*, 20, 1926, p. 353.
- ¹³ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 79, 1923, p. 226.
- ¹⁴ S. W. Wooldridge, *Proc. Geol. Assoc.*, 35, 1924, p. 377.
- ¹⁵ H. B. Milner, *Quart. Journ. Geol. Soc.*, 78, 1922, p. 358.
- ¹⁶ I. S. Double, *Proc. Geol. Assoc.*, 35, 1924, p. 340.
- ¹⁷ W. G. Shannon, *Geol. Mag.*, 64, 1927, p. 147.

General Reference.

C. Raeburn and H. B. Milner, "Alluvial Prospecting." (Murby, London), 1927, p. 432.

STEATITE (Talc)

Chem. Comp. $3\text{MgO} \cdot 4\text{SiO}_2 \cdot \text{H}_2\text{O}$.

System. Orthorhombic ? (Pseudo-hexagonal).

Habit. (001) laminæ in masses.

Structure. Crystalline, massive, foliated.

Cleavage. Perfect || (001).

Fracture. Difficult.

Hardness. 1.

Spec. Grav. 2.7-2.8.

Lustre. Pearly, resinous.

Colour. White, cream, green. Transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low, $\alpha = 1.539$, $\beta = 1.589$, $\gamma = 1.589$. Birefringence strong, $\gamma - \alpha = 0.050$. Optically biaxial, negative. Optic axial plane || (100). $Bxa = X = c$ nearly \perp (001). $2V = 6^\circ - 30^\circ$. $2E = 9^\circ - 48^\circ$. (Optic axial angle often nearly zero due to compound laminæ.) Dispersion weak, $\rho > v$.

Characters in Sediments. Grains of steatite are identified by their colour, micaceous habit, usual semi-transparency, low R.I. and strong birefringence. Often exhibits very small optic axial angle due to superimposition of laminæ, hence distinction from muscovite. Difficult to diagnose microscopically *per se* unless anticipated from associated minerals or known provenance of sediment.

Occurrence. In the Lower Cambrian, Massif de Ste. Croix, Central Poland;¹ in sediments of Cretaceous to Miocene age, Cypress Hills, Saskatchewan, Canada;² in sands (Miocene) of Turin, Italy;³ in sands of Bahia, Brazil.⁴

Possible Sources of Derivation. Schist, serpentine. Occasional alteration product of olivine, rhombic pyroxene etc., in basic igneous rocks.

References.

- ¹ P. Radziszewski, *Bull. Serv. géol. Pologne*, 4, 1928, p. 500.
- ² F. J. Fraser, *Summ. Rep. Geol. Surv., Canada*, 1928, p. 44B.
- ³ L. Colomba, *Atti R. Accad. Sci. Torino*, 31, 1896, p. 993.
- ⁴ A. Damour, *Bull. Soc. géol. France*, 13, 1856, p. 542.

STRONTIANITE

Chem. Comp. $\text{SrO} \cdot \text{CO}_2$.

System. Orthorhombic.

Habit. Prismatic, acicular. Often twinned on (110), lamellar or pseudo-hexagonal.

Structure. Crystalline. Fibrous, granular.

Cleavage. Perfect || (110), poor || (010).

Fracture. Uneven, brittle.

Hardness. 4.

Spec. Grav. 3.7.

Lustre. Vitreous, resinous.

Colour. Colourless, white, green, yellow. Transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. low for $\alpha = 1.520$, high for $\beta = 1.667$, $\gamma = 1.667$. Birefringence very strong, $\gamma - \alpha = 0.147$. Optically biaxial, negative. Optic axial plane || (010). $Bxa = X = c \perp (001)$. $Z = a$. Straight extinction || length in prismatic grains. $2V = 7^\circ$. $2E = 12^\circ$. Dispersion weak, $\rho < \nu$. Non-pleochroic.

Characters in Sediments. The acicular habit, contrasted R.I. values for α and γ , very strong birefringence and negative biaxial figure of small angle, help to diagnose this mineral, but its presence should if possible be confirmed by chemical tests (crimson flame of Sr and solubility in HCl). It is not a common mineral in nature, still less so in sediments.

Occurrence. In Eocene, Oligocene, Miocene-Pliocene and Pleistocene deposits, Colorado, U.S.A.¹

Possible Sources of Derivation. Mineralised veins and concretions in limestones.

Reference.

¹ T. L. Bailey, *Univ. Texas Bull.* 2333, 1923.

SULPHUR

Chem. Comp. S.

System. Orthorhombic.

Habit. Prismatic, pyramidal, tabular. Interpenetration twins on (101) more rarely on (110) or (011).

Structure. Crystalline, massive, granular.

Cleavage. Imperfect || (001), (110), (111).

Fracture. Conchoidal.

Hardness. 2.

Spec. Grav. 2.06.

Lustre. Resinous.

Colour. Yellow. Translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. very high, $\alpha = 1.957$, $\beta = 2.037$, $\gamma = 2.245$. Birefringence extreme, $\gamma - \alpha = 0.288$. Optically biaxial, positive. Optic axial plane || (010). $Bxa = Z \perp (001)$. $X = a$. $2V = 69^\circ$. Dispersion weak, $\rho < \nu$.

Characters in Sediments. Native sulphur is rare in sediments (other than authigenic), but may be searched for in suitable circumstances,

generally as granules, identified by colour, R.I. and form. Determinable crystals in sediments are rare. The mineral is only to be anticipated where a local and distinctive rock suite (usually volcanic) is laid under contribution to detrital sediment.

Occurrence. From Carboniferous Rocks, Texas, U.S.A.^{1, 2}

Possible Sources of Derivation. Recent volcanoes. Mineral veins. Hot springs etc.

References.

¹ E. A. Smith, *Science*, 3, 1896, p. 657.

² E. M. Skeats, *Univ. Texas Mineral Survey, Bull.* 11, 1902, p. 29.

TALC

See Steatite, p. 343.

THULITE

(VARIETY OF ZOISITE, *q.v.* p. 356)

TITANITE (Sphene)

[Pl. 28 c, D, facing p. 341.]

Chem. Comp. $\text{CaO} \cdot \text{SiO}_2 \cdot \text{TiO}_2$.

System. Monoclinic.

Habit. Euhedral, prismatic, diamond- or wedge-shaped (flattened \parallel (001) and (111)). Frequently twinned on (100).

Structure. Crystalline.

Cleavage. Good \parallel (110), imperfect \parallel (100) and ($\bar{1}$ 12), rare \parallel (111). Parting \parallel (221) twin lamellæ.

Fracture. Irregular.

Hardness. 5-5.5.

Spec. Grav. 3.4-3.56.

Lustre. Vitreous, resinous.

Colour. Brown, brownish-yellow, orange, yellow-green, olive-green. Translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Moderate conductor.

Opt. Prop. R.I. very high, $\alpha = 1.900$, $\beta = 1.907 \pm$, $\gamma = 2.034$. Birefringence very strong, $\gamma - \alpha = 0.134$. Optically biaxial, positive. Optic axial plane \parallel (010). $Bxa = Z$ practically \perp (102), Λ about 51° with cleavage (c) in obtuse angle β . $Y = b$. Optic axial angle small but variable, $2V = 27^\circ \pm$. $2E = 52\frac{1}{2}^\circ$. Total extinction seldom observed with white light, colour changes being from "ultra-blue" to yellows and reds. Very strong axial dispersion, $\rho > v$, usually well seen in the somewhat peculiar interference figure (with convergent light); this figure is generally incomplete in detrital grains, but the isogyres of the partial figure may prove of diagnostic value. In this connexion A. Brammall writes "the brush is broad, merely a dark grey shadow, and is reddish on the convex side, bluish on the concave side. . . ." With

Wratten light-filters . . . "each colour applied in turn yields a sharper, darker brush free from marginal colour contrasts. The approximate position of the brushes for red and green respectively can usually be fixed accurately enough to verify the dispersion formula. . . ." "The direction of maximum absorption is 'slow' and rarely the direction of elongation."¹² Occasionally pleochroic in strongly coloured varieties: X=yellow or colourless, Y=greenish pink or brownish yellow, Z=salmon pink or pale yellow.

Characters in Sediments. The commonest type of detrital titanite is the irregularly shaped, slightly rounded or acutely ragged grain determined principally by (110) cleavage; the diamond-shaped grains, either with equidimensional margins or elongated somewhat like a tetragonal bipyramid, are also observed. Such grains have been figured by E. F. Newton.¹ In colour titanite is usually brown to brownish-yellow, often with dusky interior; or the colour may appear bleached; more uncommon are the orange, yellow-green and olive-green types. Some crystals are observed to be traversed by a network of cracks due mainly to fracture, to a lesser degree to the combination of (110) and (100) cleavages. Diagnosed chiefly by the high R.I., colour, absence of extinction, interference figure and inclined dispersion, though there are many cases where positive diagnosis is difficult.

Possible Sources of Derivation. Granites, intermediate igneous rocks, metamorphic rocks such as gneisses, schists and altered limestones. When abundant probably authigenic.

Occurrence. "Some of the horizons at which it is relatively plentiful are the Bunter, the Keuper, the Middle and Upper Lias, the Inferior Oolite . . . the Callovian, Kimmeridgian, Portlandian, Aptian, Albian and the Eocene, Pliocene and Glacial deposits generally."² In the New Red Sandstone of the West of England;³ in the Northampton Ironstone;⁴ in the Upper Kimmeridge Clay and Portland Sand of Buckinghamshire etc.;⁵ in the Lower Greensand of Aspley Guise, Bedfordshire⁶ and Great Gransden, Huntingdonshire;⁷ in the Sandgate Beds of Surrey;⁸ in the Fuller's earth (Lower Greensand) of Nutfield, Surrey;⁹ in the Red Crag, Chillesford Beds, Upper Crag and *Leda myalis* Bed of East Anglia (Pliocene);¹⁰ in the dune sands of South Wales;¹¹ in the Dartmoor detritals.¹²

References.

- ¹ *Proc. Geol. Assoc.*, 48, 1937, Pl. 14 and 16.
- ² P. G. H. Boswell, "The Rarer Detrital Minerals of British Sedimentary Rocks," *Trans. Geol. Soc. Glasgow*, 18, 1926-27, p. 136.
- ³ H. H. Thomas, *Quart. Journ. Geol. Soc.*, 65, 1909, p. 238.
- ⁴ J. G. A. Skerl, *Proc. Geol. Assoc.*, 38, 1927, p. 383.
- ⁵ E. Neaverson, *Proc. Geol. Assoc.*, 36, 1925, p. 251.
- ⁶ R. H. Rastall, *Geol. Mag.*, 1919, p. 267, and Fig. 6.
- ⁷ R. H. Rastall, *op. cit.*, p. 218.
- ⁸ G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915-16, p. 93.
- ⁹ E. F. Newton, *op. cit.*, p. 179.
- ¹⁰ I. S. Double, *Proc. Geol. Assoc.*, 35, 1924, p. 342.
- ¹¹ A. Stuart, *Proc. Geol. Assoc.*, 35, 1924, p. 324.
- ¹² A. Brammall, *Proc. Geol. Assoc.*, 39, 1928, p. 39.

TOPAZ

[Pl. 29 A, facing p. 348.]

Chem. Comp. $2(\text{Al}, \text{F})\text{O} \cdot \text{SiO}_2$.*System.* Orthorhombic.*Habit.* Prismatic, with pyramidal terminations, domes and basal plane. Often vertically striated.*Structure.* Crystalline, granular.*Cleavage.* Perfect basal \parallel (001), imperfect \parallel to (201) and (021).*Fracture.* Irregular, subconchoidal.*Hardness.* 8.*Spec. Grav.* 3.58.*Lustre.* Vitreous, subresinous; pearly on (001).*Colour.* Colourless, yellow, blue, red, green. Transparent.*Mag. Prop.* Non-magnetic.*Elect. Prop.* Non-conductor.*Opt. Prop.* R.I. high, $\alpha = 1.619$, $\beta = 1.620$, $\gamma = 1.627$. Birefringence weak, $\gamma - \alpha = 0.008$. Optically biaxial, positive. Optic axial plane \parallel (010). $Bxa = Z \parallel c$, \perp (001). $Y \parallel b$, $X \parallel a$. $2V \approx 60^\circ$ (varies). Prismatic sections give straight extinction. Optical anomalies sometimes noted in large alluvial grains. Pleochroism noted in certain thick grains, $X =$ brownish yellow, $Y =$ yellowish-pink, $Z =$ violet-pink. Dispersion $\rho > \nu$.*Characters in Sediments.* Subangular, irregularly-shaped grains are commonest in sediments, euhedra being rare. Basal grains are of frequent occurrence (due to dominant cleavage) and these show good interference figures. Inclusions are not uncommon, these being mostly fluid; ilmenite and hematite inclusions have also been observed. Detrital topaz is diagnosed chiefly by its glassy, irregular habit, high relief, often a delicate bluish tinge, especially on fractured surfaces, and striking yellow and red interference colours. Many grains will be found to yield beautiful positive interference figures.*Occurrence.* In the Millstone Grit of Yorkshire;¹ in the Lower Coal Measures of South-West Lancashire;² in the New Red Sandstone of the West of England;³ in the Upper Kimmeridge Clay and Portland Sand of Dorset, Wiltshire and Oxfordshire;⁴ in the Chalky-Jurassic Boulder Clay at Ipswich;⁵ in the Lower Greensand of the Dorking-Leith Hill district;⁶ in the Cretaceous, Eocene of the Haldon Hills, Devonshire;⁷ in the Suffolk Boxstones;⁸ in the later Tertiary deposits of East England;⁹ in the Pliocene deposits of Cornwall;¹⁰ in the Plateau deposits and Beach deposits of S.E. Devonshire;¹¹ in the shore sand of St. Ives Bay, Cornwall;¹² in the dune sands of South Wales;¹³ in the Dartmoor detritals.¹⁴*Possible Sources of Derivation.* Granite, gneiss and other contact metamorphic rocks.**REMARKS.**—Topaz is seldom an abundant mineral in detrital sediments and it tends to be local. It may sometimes be easily confused with andalusite, which it resembles in certain crystallographic and physical properties; it may be differentiated from that species by its cleavage, general absence of pleochroism, optically positive character and transparency, andalusite being so commonly clouded with alteration products and carbonaceous matter. On the other hand, where topaz has altered to damourite (hydro-mica), its distinction from sericitised andalusite is a matter of considerable difficulty.*References.*¹ A. Gilligan, *Quart. Journ. Geol. Soc.*, 75, 1919, p. 264, 273.² A. Gilligan, *Proc. Liverpool Geol. Soc.*, 1933.³ H. H. Thomas, *Quart. Journ. Geol. Soc.*, 65, 1909, p. 235.⁴ E. Neaveyron, *Proc. Geol. Assoc.*, 36, 1925, p. 240.

- ⁵ P. G. H. Boswell, *Journ. Roy. Anthropol. Inst.*, 63, 1923, p. 229.
- ⁶ H. A. Hayward, *Proc. Geol. Assoc.*, 43, 1932, p. 1.
- ⁷ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 79, 1923, p. 210, 214, 226, 227.
- ⁸ P. G. H. Boswell, *Geol. Mag.*, 1916, p. 250.
- ⁹ I. S. Double, *Proc. Geol. Assoc.*, 35, 1924, p. 332.
- ¹⁰ H. B. Milner, *Quart. Journ. Geol. Soc.*, 78, 1922, p. 359, 362.
- ¹¹ W. G. Shannon, *Geol. Mag.*, 64, 1927, p. 147.
- ¹² T. Crook and G. M. Davies, *Geol. Mag.*, 1909, p. 122.
- ¹³ A. Stuart, *Proc. Geol. Assoc.*, 35, 1924, p. 325.
- ¹⁴ A. Brammall, *Proc. Geol. Assoc.*, 39, 1928, p. 38.

General Reference.

- C. Raeburn and H. B. Milner, "Alluvial Prospecting." (Murby, London), 1927, p. 435 and Pl. 28 (for alluvial topaz).

TOURMALINE

[Pl. 5, facing p. 172, and Pl. 29 B, facing p. 348.]

Chem. Comp. $\text{Na}_2\text{O} \cdot 0.8\text{FeO} \cdot 0.8\text{Al}_2\text{O}_3 \cdot 4\text{B}_2\text{O}_3 \cdot 16\text{SiO}_2 \cdot 5\text{H}_2\text{O}$.

System. Trigonal.

Habit. Prismatic, often with vertical striations, irregular terminations.

Structure. Crystalline, massive, compact; frequently radiating or in parallel growth.

Cleavage. Imperfect $\parallel (11\bar{2}0)$ (rhombohedral) and poor $\parallel (10\bar{1}1)$. Basal parting.

Fracture. Subconchoidal.

Hardness. 7-7.5.

Spec. Grav. 2.98-3.20.

Lustre. Vitreous, resinous.

Colour. Brown, blue, green, black, brownish-black, pink; rarely colourless. Transparent, translucent and opaque (rare).

Mag. Prop. Weakly magnetic.

Elect. Prop. Moderate conductor.

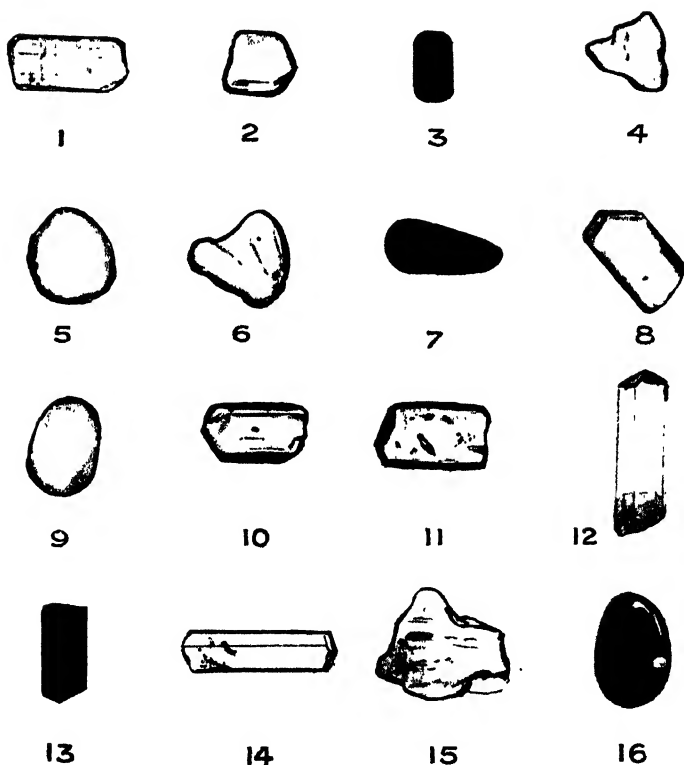
Opt. Prop. R.I. high, $\epsilon = 1.658$, $\omega = 1.698$. Binefringence strong, $\omega - \epsilon = 0.040$. Optically uniaxial, negative. Length fast. Occasionally grains show anomalous biaxial interference figure, when $2E = 10^\circ$. Prismatic grains give straight extinction. Pleochroism varies with colour, being normally most intense in brown varieties: $\omega = \text{green}$, yellow-brown, blue or black $> \epsilon = \text{yellow}$, violet or colourless. Maximum absorption in prismatic grains \perp vibration plane of polariser.

Characters in Sediments. An ubiquitous species, occurring principally in three forms, prismatic with varied terminations, basal or quasi-basal (usually well rounded) and irregular fractured grains. The prismatic varieties may be terminated by rhombohedra and basal parting, but are often void of terminal faces, being frequently bounded by parting or irregular fracture. Pseudo-hexagonal plates flattened $\parallel (0001)$ and modified by $(11\bar{2}0)$ faces have been described, but are rare; such grains and similar basal types exhibit good uniaxial interference figure. Colour and pleochroism vary greatly, the brown and dark coloured grains normally showing the strongest pleochroism; blue tourmaline (indicolite) is invariably weak in this respect. Particoloured brown and blue or brown and green mica-like flakes are frequent. Inclusions are often noted and may be cavities, zircon, rutile (both granules and needles), opaque particles, cassiterite, quartz, topaz, fluorite, feldspar, muscovite (gilbertite), anatase, brookite and water-clear titanite.⁵ Prismatic grains often show striations \parallel principal axis. Zoning is an occasional feature (e.g. Dartmoor). The mineral is nearly always remarkably free from decomposition products, grains being normally translucent.



A. TOPAZ

- A. 1, 2 Alluvials, Nigeria [x 45]
 A. 3, Lower Greensand, Poulshott Green, N.W. Wilts. [x 15]
 A. 4 Phocine Sand, St. Keverne, Cornwall [x 15]



B. TOURMALINE.

- 1, Tunbridge Wells Sand, Tunbridge Wells, Kent [x 70]
 4 Ashdown Sand, Hastings, Sussex [x 50]
 5, 6 Glacial Sands, Withybush, Havertford west, Pembrokeshire [x 40]
 7 Blown Sand, Newgale, Pembrokeshire [x 70]
 8 Eocene Sand, Bronlley, Kent [x 70]
 9 Blown Sand, Rosslare, Co. Wexford [x 40]
 10 Recent Sands, Brazil [x 70]
 11 Bagshot Sand, Hampstead, London [x 40]
 12 Moringa Sands (Phocene), Trinidad [x 70]
 13, 14 Phocene Sands, St. Erth, Cornwall [x 70]
 15, 16. Phocene Sands, St. Erth, Cornwall [x 40]

Occurrence. Ubiquitous in detrital sediments at most geological horizons in Great Britain. A brief selection from the prolific records of this mineral covers most of the varieties:—in the Bunter Pebble Bed of the West of England;¹ in the New Red Sandstone of the West of England;² in the Cretaceous and Tertiary outliers of the West of England;³ in the Pliocene deposits of Cornwall;⁴ in the Dartmoor detritals.⁵

Possible Sources of Derivation. Pneumatolytic rocks, acid igneous rocks, pegmatites, schists, gneisses, phyllites.

References.

- ¹ H. H. Thomas, *Quart. Journ. Geol. Soc.*, 58, 1902, p. 624.
- ² H. H. Thomas, *Quart. Journ. Geol. Soc.*, 65, 1909, p. 233-4.
- ³ P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 79, 1923, p. 208, 211, 213, 215, 218, 226.
- ⁴ H. B. Milner, *Quart. Journ. Geol. Soc.*, 78, 1922, p. 358, 361, 363.
- ⁵ A. Brammall, *Proc. Geol. Assoc.*, 39, 1928, p. 34.

General References.

- A. Brammall and H. F. Harwood, "Tourmalinization in the Dartmoor Granite." *Mineral. Mag.*, 20, 1925, p. 319.
 C. Raeburn and H. B. Milner, "Alluvial Prospecting." (Murby, London), 1927. p. 437 and Pl. 29 (for alluvial tourmaline and varieties).

TREMOLITE [Pl. 30 A, facing p. 352.] (AMPHIBOLE GROUP)

Chem. Comp. $2\text{CaO} \cdot 5\text{MgO} \cdot 8\text{SiO}_2 \cdot \text{H}_2\text{O}$.

System. Monoclinic.

Habit. Prismatic, euhedral or irregular; acicular.

Structure. Crystalline, fibrous.

Cleavage. Well developed $\parallel (110)$, more rarely $\parallel (100)$ and (010) .

Fracture. Subconchoidal, uneven, developed \perp prismatic cleavage.

Hardness. 5-6.

Spec. Grav. 3.33.

Lustre. Vitreous; pearly on cleavage flakes.

Colour. Colourless, white, grey, occasionally pink or mauve (manganese) or pale green (ferrous iron).

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. high, $\alpha = 1.600$, $\beta = 1.616$, $\gamma = 1.627$. Birefringence strong, $\gamma - \alpha = 0.027$. Optically biaxial, negative. Optic axial plane $\parallel (010)$. $Y \parallel b$, $Z \wedge c = 17^\circ \pm$. Length slow. Bxo inclined at low angle to c axis. $2V = 80^\circ$. Slight dispersion of the bisectrices in the plane (010) . Practically non-pleochroic in colourless varieties, but perceptibly pleochroic if mauve or green: $X =$ pale yellow, $Y =$ greenish-yellow, $Z =$ green. Dispersion weak, $\rho < \nu$.

Characters in Sediments. Diagnosis of detrital tremolite rests chiefly on its "hornblende" character minus the colour of that mineral, on R.I., extinction angle and birefringence; it frequently exhibits the same sort of "ragged ends" typical of hornblende. Grey or white prismatic grains are the commonest; inclusions may be biotite or carbonaceous matter. Superficial alteration to *steatite* (p. 343) (noted with high power objective as minute powdery flakes or scales) is not uncommon. Fibrous varieties (*asbestos*) not recorded from detrital sediments.

Occurrence. In sands of Chipstead, Surrey (?Pliocene);¹ in later Tertiary deposits, East England;² in recent sands of S.W. Pembrokeshire and S. Cornwall;³ in recent deposits of Pavia etc., northern Italy;⁴ in Pleistocene-Recent deposits of the Lazard area, San Joaquin Valley, California;⁵ in Glacial Sands of the Menai Straits (Anglesey), of Haverfordwest, Pembrokeshire;⁶ in Glacial deposits of Kimpton, Hertfordshire;⁷ in Beach Sands, Cedar Point, Ohio, U.S.A.⁸

Possible Sources of Derivation. Metamorphic rocks, crystalline schists. Metamorphosed magnesian limestone. From alteration of minerals in gabbros and peridotites; from the disintegration of serpentine.

REMARKS.—Tremolite is at first likely to be confused with diopside, but is soon distinguished from that mineral by its lower extinction angle, lower R.I. and (usually) lower interference tint; also by the general absence of inclusions frequently noted in diopside.

References.

- ¹ G. M. Davies, *Proc. and Trans. Croydon Nat. Hist. Soc.*, 1915-16, p. 77, 91.
- ² I. S. Double, *Proc. Geol. Assoc.*, 35, 1924, p. 335.
- ³ Author's observations.
- ⁴ E. Tacconi, *Rend. R. Ist. lombardo*, ser. 2, vol. 34, 1901, p. 873.
- ⁵ R. D. Reed and J. P. Bailey, *Bull. Amer. Assoc. Petrol. Geol.*, 11, 1927, p. 363.
- ⁶ Observations of G. M. Part and the author.
- ⁷ Observation of G. C. Flower.
- ⁸ F. J. Pettijohn and J. D. Ridge, *Journ. Sed. Pet.*, 3, 1933, p. 92.

UVAROVITE (GARNET GROUP)

Chem. Comp. $3\text{CaO} \cdot \text{Cr}_2\text{O}_3 \cdot 3\text{SiO}_2$.

System. Isometric.

Habit. Dodecahedral (110), trapezohedral with hexoctahedral modifications. Striations on (110) faces.

Structure. Crystalline.

Cleavage. None.

Fracture. Irregular.

Hardness. 7.5.

Spec. Grav. 3.4.

Lustre. Vitreous, resinous.

Colour. Emerald green. Transparent, translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. very high, $n = 1.838$. Isotropic. Rarely anisotropic.

Characters in Sediments. Subangular and rounded dodecahedral grains (or more complex forms) are found in certain specialised sedimentary environments. Diagnosed by colour, high R.I. and general isotropism. Tendency to alter to chloritic matter.

Occurrence. In sands of the Kettleman Hills, California, U.S.A.¹

Possible Sources of Derivation. Gneiss, serpentine, metamorphosed limestone.

REMARKS.—Uvarovite is rare. Often associated with chromite.

Reference.

- ¹ M. N. Bramlette, *Bull. Amer. Assoc. Petrol. Geol.*, 18, 1934, p. 156a.

VESUVIANITE (Idocrase)

Chem. Comp. $2(\text{Mg,Fe})(\text{OH})_2 \cdot 2\text{Al}_2\text{Si}_2\text{O}_7 \cdot 5\text{Ca}_2\text{SiO}_4$. Be may be present.

System. Tetragonal: holosymmetric.

Habit. Prismatic, pyramidal, the latter sometimes being a combination of prism (100) with (111) and (311); (110) often developed.

Structure. Crystalline, columnar or massive.

Cleavage. Indistinct || (110), poor || (100) and (001).

Fracture. Conchoidal.

Hardness. 6.5.

Spec. Grav. 3.35-3.45.

Lustre. Vitreous.

Colour. Brown, red, green, pale blue or yellow (rare). Translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. high, $\epsilon = 1.705$, $\omega = 1.713$. Birefringence weak, $\omega - \epsilon = 0.008$. Optically uniaxial, negative. Rarely biaxial, with variable optic axial angle: $2E = 30^\circ - 60^\circ$. Straight extinction. Elongation fast. Pleochroism varies, $\omega > \epsilon$: in green varieties, yellow-green to colourless; in brown varieties, yellow-brown to brownish-grey; in blue varieties, dark blue to colourless; in red varieties, red to colourless or grey.

Characters in Sediments. More detrital vesuvianite is required for study before the average characteristics of this mineral in sediments can be definitely stated. Thus far observations indicate a tendency for the grains to be prismatic, brown or greenish-brown in colour, weakly pleochroic, but in all cases typified by strong relief and weak birefringence. Other optical properties vary, both uniaxial positive and negative forms, together with biaxial crystals, being observed. [N.B.—The positive form may be the variety *viluite*.] The uneven distribution of the colouring matter has been noted in one or two instances, also colour-zoning.

Occurrence. Possibly in the dune sands of South Wales;¹ in superficial deposits derived from the Bodmin Granite, North Cornwall;² in Pleistocene-Recent deposits of the Lazard area, San Joaquin Valley, California;³ in sands on the south shore of Long Island, New Jersey;⁴ in the Limburg Loess.⁵

Possible Sources of Derivation. Thermally metamorphosed limestone (in association with epidote, garnet, diopside etc.); crystalline schist; pegmatite; gneiss.

REMARKS.—Viluite is a rare variety of vesuvianite, containing B_2O_3 . Usually exhibits a positive biaxial interference figure.

References.

¹ A. Stuart, *Proc. Geol. Assoc.*, 35, 1924, p. 322.

² Author's observations

³ R. D. Reed and J. B. Bailey, *Bull. Amer. Assoc. Petrol. Geol.*, 11, 1927, p. 363

⁴ R. J. Colony, *Journ. Sed. Pet.*, 2, 1932, p. 150.

⁵ J. H. Druif, "Over het ontstaan der Limburgsche Löss in verband met haar mineralogische Samenstelling." *Utrecht*, 1927.

VILUITE

(VARIETY OF VESUVIANITE (IDOCRASE), *q.v.* supra)

WOLFRAMITE

Chem. Comp. $(\text{Fe}, \text{Mn})\text{O} \cdot \text{WO}_3$.

System. Monoclinic.

Habit. Prismatic, bladed, tabular (100).

Structure. Crystalline, massive, lamellar, granular.

Cleavage. Perfect \parallel (010). Parting \parallel (100) and (102).

Fracture. Uneven.

Hardness. 5-5.5.

Spec. Grav. 7.2-7.5.

Lustre. Submetallic, brilliant on (010), dull on other faces.

Colour. Brown, greyish-black, black. Translucent to opaque.

Mag. Prop. Moderately magnetic (Fe-bearing variety).

Elect. Prop. Moderate conductor.

Opt. Prop. R.I. very high, $\alpha = 2.26$, $\beta = 2.32$, $\gamma = 2.42$ (Li). Birefringence very strong, $\gamma - \alpha = 0.16$. Optically biaxial, positive. Optic axial plane \perp (010). $Bxa = Z \wedge c$ 17° - 21° . Optic axial angle large. Pleochroism variable: X = yellow green < Y = pale green, brown < Z = grass green, brown red.

Characters in Sediments. Generally occurs as irregular greyish-black "metallic" grains, opaque except on thin edge, when the very high R.I. and (occasionally) pleochroism can be detected, the latter property being characteristic of the Mn-bearing variety (Huebnerite). In favourable circumstances (010) cleavage flakes, if sufficiently translucent, can be confirmed by the extinction angle (17° - 21°).

Occurrence. Dune sands of South Wales (?);¹ in the alluvials of the Bufumbira district, Uganda;² in the Malay Alluvium;³ in black sands, Nome Creek, Alaska;⁴ in recent deposits, Bodmin Moor, Cornwall.⁵

Possible Sources of Derivation. Mineral lodes.

REMARKS.—Wolframite is really a group name comprising minerals varying in composition from FeWO_4 (ferberite) to MnWO_4 (huebnerite). Associated minerals are usually manganese and tin ores, also fluorite.

References.

¹ A. Stuart, *Proc. Geol. Assoc.*, 35, 1924, p. 324.

² A. D. Combe and W. C. Simmons, *Geol. Surv. Uganda*, 3, 1933.

³ W. R. Dunstan, *Bull. Imp. Inst.*, 14, 1916, p. 321.

⁴ A. S. Wilkerson, *Amer. Min.*, 15, 1930, p. 77.

⁵ Author's observations.

WOLLASTONITE

[Pl. 30 B, facing p. 352.]

Chem. Comp. $\text{CaO} \cdot \text{SiO}_2$.

System. Monoclinic.

Habit. Tabular (100) or (001).

Structure. Crystalline. Massive.

Cleavage. Perfect \parallel (100), good \parallel (001); imperfect \parallel ($\bar{1}01$) and (102).

Fracture. Uneven.

Hardness. 5.

Spec. Grav. 2.9.

Lustre. Vitreous, pearly on cleavage faces.

Colour. Colourless, white, grey, yellow. Transparent to translucent.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. high, $\alpha = 1.620$, $\beta = 1.632$, $\gamma = 1.634$. Birrefringence moderate, $\gamma - \alpha = 0.014$. Optically biaxial, negative. Optic axial



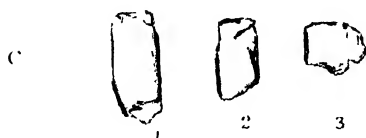
A TREMOLITE.

- A 1. Glacial Sand, Menai Straits (Anglesea) (X 60).
 A 2. Glacial Sand, Haverfordwest, Pembrokeshire (X 4).



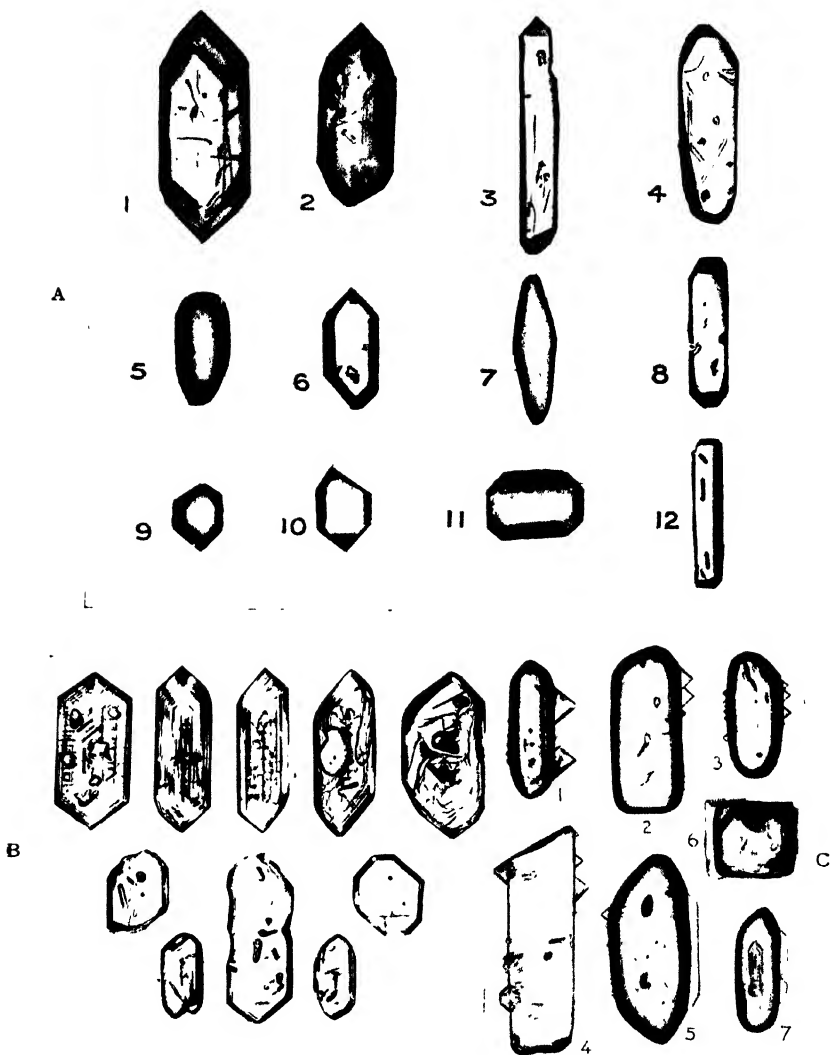
B. WOILASTONITE.

(X B. Locality not known.)



C ZOISITE.

- C 1. Miocene Sand, Santa Fe Springs, Calif., U.S.A. (X 45).



A-C. ZIRCON.

- A 1, 2 Alluvials W Africa. [x 100.]
 A 3 Bagshot Sand, Hampstead Heath, London. [x 100.]
 A 4, 5 Lower Greensand, N.W. Wiltshire. [x 100.]
 A 6 Wealden Sand, Shotover Hill, Oxford. [x 100.]
 A 7, 8, 12 Tunbridge Wells Sand, Kent. [x 100.]
 A 9 11 Ashdown Sand, Hastings, Sussex. [x 100.]
 B Typical Crystals and Fragments of Dartmoor Zircon; grade-size . 0.1 4 mm.
 (From brush-drawings by A. Brammall.)
 C. Zircon with outgrowths :
 1-3. Millstone Grit, Yorkshire. [x 150.]
 4-6. Middle Jurassic, Yorkshire. [x 150.]
 7. Lower Carboniferous, Northumberland. [x 150.]

plane $\parallel (010)$. $Bxa = X \wedge c$ at 32° in acute angle β . Elongation $\parallel b$. Y near b . Optic axial angle moderate: $2V = 39^\circ$. $2E = 65^\circ$. Dispersion distinct, $p > v$.

Characters in Sediments. Detrital wollastonite is determined principally by (100) and (001) cleavages. Diagnosed by careful optical measurements, in particular R.I., moderate birefringence, extinction angle and absence of pleochroism. Alteration to calcite sometimes noted.

Occurrence. In the volcanic soil of the East Indian Archipelago;¹ in shore sands, Long Island and New Jersey, U.S.A.;² in the alluvial deposits of Du Toit's Pan, West Africa.³

Possible Sources of Derivation. Metamorphosed limestone.

REMARKS.—Wollastonite is often associated with calcite, diopside, epidote, garnet, zoisite.

References.

¹ J. van Baren, *Contrib. Geol. Inst. Univ. Wageningen*, 17, 1931.

² R. J. Colony, *Journ. Sed. Pet.*, 2, 1931, p. 150

³ S. Meunier, *C.R. Acad. Sci. Paris*, 84, 1877, p. 250.

XENOTIME

Chem. Comp. $Y_2O_3 \cdot P_2O_5$.

System. Tetragonal.

Habit. Euhedral, prismatic. Twinned on (101).

Structure. Crystalline.

Cleavage. Perfect $\parallel (110)$.

Fracture. Uneven, irregular.

Hardness. 4-5.

Spec. Grav. 4.4-4.6.

Lustre. Vitreous.

Colour. Shades of brown, brownish-red, yellow. Translucent.

Mag. Prop. Moderately magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. very high, $\epsilon = 1.816$, $\omega = 1.721$. Birefringence strong, $\epsilon - \omega = 0.095$. Optically uniaxial, positive. Length slow. Compensates \perp length. Straight extinction. Pleochroism weak: ω = pale yellow, brownish-yellow, ϵ = yellow, green.

Characters in Sediments. Usually occurs as pale yellow, orange or pink, beautifully formed euhedra, doubly terminated tetragonal prisms; alternatively as rounded prismatic grains or as subangular rectangular flakes, in all cases exhibiting very high relief. The strong resemblance morphologically and optically to coloured zircon is invariable, and renders positive diagnosis of xenotime in detrital sediments a matter of great difficulty by microscopical means alone. The larger alluvial grains from recorded foreign localities afford the most promising material for study; these sometimes show patchy decomposition products recalling the cerium oxide films developed superficially on monazite.

Occurrence. In the Millstone Grit of Yorkshire;¹ in Grindstones from the Yorkshire Coal Measures;² in the Lower Permian at Conisborough;³ in the Bunter Pebble Bed of the West of England;⁴ in the Lower Greensand of Great Gransden, Huntingdonshire, and of Apsley Guise, Bedfordshire;⁵ in the Pliocene Sands of St. Agnes and St. Erth, Cornwall;⁶ in Pleistocene deposits of the lower part of the Great Ouse Basin;⁷ in beach sands, Florida, U.S.A.⁸

(N.B.—In each of the above cases, the mineral is only recorded as a possible alternative to certain abnormal types of zircon.)
Possible Sources of Derivation. Granites, pegmatites, intermediate rocks; less commonly gneiss.

REMARKS.—Xenotime is an exceedingly difficult mineral to differentiate from coloured zircon in detrital sediments by ordinary microscopical methods; recourse to spectroscopic methods is essential to its positive determination. During the last few years there has been an increasing tendency on the part of British petrographers to give coloured zircon priority of record rather than indicate a doubtful occurrence of xenotime and short of definite chemical and spectroscopic proof of this species, this policy would seem to be more in keeping with the observed facts. The extreme rarity of the mineral, or of the equivalent coloured zircon for that matter, makes research into its detrital occurrences a difficult task. The principal differences from zircon consist in its weak magnetic properties, lesser tendency to exhibit inclusions, normal absence of zoning, lower R.I. and softer nature: the latter may to some extent account for its rarity.

References.

- ¹ A. Gilligan, *Quart. Journ. Geol. Soc.*, 75, 1919, p. 267.
- ² H. P. Lewis and W. J. Rees, *Geol. Mag.*, 63, 1926, p. 13.
- ³ A. Gilligan, *Proc. Yorks. Geol. Soc.*, 19, 1918, p. 255.
- ⁴ H. H. Thomas, *Quart. Journ. Geol. Soc.*, 58, 1902, p. 623.
- ⁵ R. H. Rastall, *Geol. Mag.*, 1919, p. 218, 268.
- ⁶ H. B. Milner, *Quart. Journ. Geol. Soc.*, 78, 1922, p. 357, 360.
- ⁷ R. H. Rastall, *Quart. Journ. Geol. Soc.*, 82, 1926, p. 116.
- ⁸ J. H. C. Martens, *Bull. Geol. Soc. Amer.*, 46, 1935, p. 1580.

General References.

- O. A. Derby, *Mineral. Mag.*, 11, 1897, p. 308.

In connexion with the possibility of occurrence and methods of diagnosing xenotime, see A. Brammall and H. F. Harwood, *Mineral. Mag.*, 20, 1923, p. 29. On methods of isolating and confirming xenotime in sediments, see J. Van der Lingen and A. R. E. Walker, *Trans. Geol. Soc. S. Africa*, 28, 1925, p. 69.

ZIRCON

[Pl. 31, facing p. 353.]

Chem. Comp. $\text{ZrO}_2 \cdot \text{SiO}_2$.

System. Tetragonal.

Habit. Euhedral; prismatic; bipyramidal. Prisms usually square or elongated in the direction of the principal axis, then terminated by pyramid faces (111). Twinning rare.

Structure. Crystalline.

Cleavage. Imperfect || (110), poor || (111).

Fracture. Conchoidal.

Hardness. 7·5.

Spec. Grav. 4·5–4·7.

Lustre. Adamantine, vitreous.

Colour. Colourless, yellow, brown, pink, mauve, purple, rarely green.

Mag. Prop. Non-magnetic.

Elect. Prop. Non-conductor.

Opt. Prop. R.I. very high, $\epsilon = 1·991$, $\omega = 1·936$. Birefringence strong, $\epsilon - \omega = 0·055$. Optically uniaxial, positive. Length slow. Occasionally abnormal biaxial crystals are met with. Straight extinction. Pleochroic in thick crystals and strongly coloured varieties.

Characters in Sediments. A common species, varying considerably in form. The prevalent type of grain is colourless, prismatic (100) or (110) or both, with pyramidal terminations (111), (331) etc. Basal grains (flattened || (001)) are scarce. Fractured grains are common, but sharply angular fragments are rare, zircon nearly always exhibiting a certain degree of rounding. Exceptionally, outgrowths on prismatic crystals giving a "sawfish" type, have been described by J. A. Butterfield (reference below). Zoning is often observed and has been fully discussed by A. Brammall (reference below). The presence of inclusions, sometimes arranged parallel to the length of the crystal, at other times irregularly distributed, is a common feature. Inclusions may be fluid, glassy, negative crystals, or consist of minerals such as apatite and possibly xenotime. Inclusions within inclusions have also been observed. A. Brammall records gas-filled cavities, opaque dust in the form of stringers, clots and cloud-like suspensions, also minute zircons, monazite, hematite, quartz, apatite and rarely rutile and biotite, from the Dartmoor detritals (*op. cit.*). Occasionally the grains have a dusky appearance due to the crowding of inclusions, *not* to decomposition products. Large grains with abnormal optical properties (biaxial interference figures, low birefringence, pleochroism and absence of inclusions) seem to be very local. Diagnosed essentially by its crystal form, high R.I., colour, inclusions and zoning (when developed).

Occurrence. Ubiquitous in detrital sediments.

Possible Sources of Derivation. Acid and intermediate igneous rocks; less commonly crystalline schists and limestones.

REMARKS.—Zircon is one of the most fascinating minerals occurring in detrital sediments, on account of its widespread occurrence throughout the geological record and its great variation in form, colour and intimate properties. To appreciate fully its significance in any given sediment, the most careful investigation of each variety present is essential, especially if any correlation or differentiation of the sediments involved is contemplated. Point is given to these remarks by the researches of A. Brammall and H. F. Harwood on the Dartmoor zircons, to which references and also to other detailed accounts of this species, are given below. Confusion with xenotime is dealt with under the heading of that mineral, p. 353.

General References.

- K. V. Chrustchoff, "Beitrag zur Kenntniss der Zirkone in Gesteinen." *Tschermaks Min. Petr. Mitt.*, 7, 1886, p. 862; also *Mem. Acad. Imp. Sci. St. Petersb.*, 43, 1894.
- H. H. Thomas, *Quartz, Journ. Geol. Soc.*, 58, 1902, p. 623 and Pl. 31, Figs. 1-9.
- A. Brammall and H. F. Harwood, *Mineral. Mag.*, 20, 1923, p. 27.
- W. Mackie, *Trans. Edinburgh Geol. Soc.*, 11, 1923, p. 200 (purple zircon).
- J. Zerndt, "Über mikroskopische Zirkone aus den Karpathensandsteinen der Umgegend von Cieszkowice." *Bull. Intern. Acad. polon.*, A, 1924, p. 219.
- P. G. H. Boswell, *Mineral. Mag.*, 21, 1927, p. 310 (distribution of purple zircon in British sediments—with many references).
- C. Raeburn and H. B. Milner, "Alluvial Prospecting." (Murby, London), 1927, p. 444 and Pl. 31 (for alluvial zircon).
- J. Zerndt, "Mikroskopische Zirkone als Leitmineralien." *Bull. Acad. Polonoise des Sciences et des Lettres, Serie A*, 1927, p. 363.
- A. Brammall, *Proc. Geol. Assoc.*, 39, 1928, p. 28, Pl. 2.
- J. A. Butterfield, "Outgrowths on Zircon." *Geol. Mag.*, 73, 1936, p. 511.

ZOISITE [Pl. 30 c, facing p. 352.]

(EPIDOTE GROUP)

Chem. Comp. $4\text{CaO} \cdot 3\text{Al}_2\text{O}_3 \cdot 6\text{SiO}_2 \cdot \text{H}_2\text{O}$.*System.* Orthorhombic.*Habit.* Prismatic, euhedral or irregular. Frequently striated || c axis.*Structure.* Crystalline.*Cleavage.* Perfect || (010); occasionally noted || (100).*Fracture.* Subconchoidal, irregular.*Hardness.* 6-6.5.*Spec. Grav.* 3.25-3.37.*Lustre.* Vitreous.*Colour.* White, grey, yellowish-brown, pale green; pink or rose-red in the variety Thulite (due to Mn).*Mag. Prop.* Non-magnetic.*Elect. Prop.* Non-conductor.

Opt. Prop. R.I. high (varies), $\alpha = 1.700$, $\beta = 1.703$, $\gamma = 1.718$. Birefringence moderate, $\gamma - \alpha = 0.018$. Optically biaxial, positive. Optic axial plane usually || (010), but is not always in the same position: sometimes noted || (001). $Bxa = Z \perp (100)$. $X || c$, $Y || b$, $Z || a$, or $X || b$, $Y || c$, $Z || a$. Straight extinction. In some examples the interference tint is deep blue, almost "ultra blue" with little or no tendency to extinction in any position. $2V$ varies from 0° to 60° , being largest when the optic axial plane is || (001). $2E = 0^\circ - 116^\circ$. Strong dispersion, $\rho < v$ or $\rho > v$. Pleochroism seen in large crystals: in the variety thulite $X = \text{pink}$ or red, $Y = \text{light pink}$, $Z = \text{yellow}$.

Characters in Sediments. Occurs as almost colourless grains generally determined by (010), hence prismatic habit is common. The high R.I. and moderate birefringence, especially the deep blue colour, are characteristic, while inclusions of amphibole microlites in the form of thin, lath-shaped, green wisps, are also a feature of this species. The mineral gives straight extinction and is practically non-pleochroic in colourless grains; a delicate pink shade with tendency to a deeper red, denotes the variety thulite which has perceptible pleochroism, but not as strong as that of andalusite (when developed in the latter mineral), with which there is a possibility of confusion. Andalusite has a lower refractive index and higher birefringence than thulite and, of course, the latter species is far less common (see below).

Occurrence. In the Portland Sands of South Wiltshire and Dorset;¹ in the Hunstanton Red Rock;² in surface deposits, sands and gravels of Cambridgeshire;³ in the Clyde alluvium;⁴ both zoisite and thulite (?) in the dune sands of South Wales;⁵ in various foreign sediments rich in epidote minerals, e.g. Miocene sands of Los Angeles basin, California, U.S.A.;⁶ in beach sands between St. John's River and St. Augustine, Florida, U.S.A.;⁷ in beach sands between Charleston, S. Carolina and Miami, U.S.A.⁸

Possible Sources of Derivation. Crystalline schists, metamorphosed basic igneous rocks; possibly from *saussurite*, an alteration product of lime-soda felspar.

REMARKS.—Zoisite is probably a far commoner detrital mineral than generally anticipated and owing to its similarity (if colourless) to other orthorhombic minerals, it is likely to be misnamed or overlooked. The variety thulite is more uncommon, though it may appear in recent sands in which the epidote species are strongly in evidence. Closely allied to zoisite is the monoclinic mineral clinozoisite (*q.v.* p. 269), whose presence

in detrital sediments is¹ probably by no means as rare as scanty records imply.

References.

- ¹ E. Neaverson, *Proc. Geol. Assoc.*, 36, 1925, p. 251.
- ² R. H. Rastall, *Geol. Mag.*, 67, 1930, p. 436.
- ³ R. H. Rastall, *Proc. Cambridge Phil. Soc.*, 17, 1913, p. 132.
- ⁴ B. H. Barrett, *Trans. Geol. Soc., Glasgow*, 17, 1926, p. 402.
- ⁵ A. Stuart, *Proc. Geol. Assoc.*, 35, 1924, p. 325.
- ⁶ Author's observations.
- ⁷ J. H. C. Martens, 19th Ann. Rep. Florida State Geol. Surv., 1928, p. 130.
- ⁸ J. H. C. Martens, *Bull. Geol. Soc. Amer.*, 46, 1935, p. 1580.

CHAPTER X.

THE PETROGRAPHY OF CONSOLIDATED SEDIMENTS.*

PRELIMINARY to any survey of sediments as consolidated rocks, distinct (with a few exceptions) from those composed of incoherent materials, some system of classification is essential as a basis of discussion. This task, however, is by no means an easy one, as most petrologists seem to have discovered. The difficulty of establishing a philosophical classification of sedimentary rocks is unquestionably greater than in the case of igneous rocks. No really satisfactory qualitative scheme which makes due allowance for the innumerable transitional varieties prevalent has yet been evolved; while a quantitative classification, temptingly foreshadowed by some possible adaptation of mechanical analysis, is still denied to the present state of knowledge.

Intimately bound up with this is the regrettably empirical nomenclature perforce adopted in the absence of something more fundamental than mere descriptive terms. In the light of modern research on both mineralogical and mechanical constitution of "sandstones," for instance, that term *per se* has ceased to have any really precise meaning. "Clay" is little better in this respect (though the old tendency to consider it synonymous with "kaolin" has at last been overcome), while "marl," "loam" and "silt" are notoriously subject to the widest interpretations.

In the following paragraphs, an attempt is made to give as precise definitions and descriptions of the conventional sedimentary rock-types as are possible, based on modern intensive laboratory studies of these materials. In the present state of knowledge probably the time is hardly yet ripe for drastic

* For completeness and convenience certain semi-consolidated and incoherent raw materials, e.g. clay, ooze, abyssal mud, etc., are included in this chapter.

revision and alteration, but the author would be failing in his duty if he did not voice in this place that discontent which workers on sedimentary rocks have long felt in regard to classification and nomenclature.

A commendable effort has recently been made to frame generally acceptable definitions of sediments by the Committee on Sedimentation, National Research Council, U.S.A. Three reports have already been published; two others (at the time of going to press) are in circulation for criticism and comment.¹ In the author's opinion these reports are invaluable in clearing the ground for generally acceptable definitions, for eliminating obsolete terms and for co-ordinating international ideas now current on sedimentary petrological nomenclature.

In view of the importance of "thin section" correlation of compact sedimentary rock-types in exploitation oil-geology hereafter discussed, it will be found that their treatment in this volume departs from custom in its bias to the technique implied by that particular application. The rock is not merely described, it is analysed, especially in mineralogical, mechanical and *structural* detail; comparative features are stressed; contrast in specific detail rather than in group-character is emphasised.

Thin section correlation has taught at least one thing; discernment of and discrimination between the finer points of varietal characters of sedimentary rock-types; the criticism may be urged that this is carrying even intensive study too far. The reply to that is the enormous amount of successful work along these lines already accomplished in many geological laboratories and the undoubted gain to the science in consequence. Sedimentary rocks are just as worthy of minute attention to detail as their igneous counterparts: when freely accorded their due in this respect, we may confidently expect that measure of enhanced interest from which advancement of knowledge alone can spring.

¹ C. K. Wentworth and H. Williams, "The Classification and Terminology of the Pyroclastic Rocks." *Bull.* 89, *Nat. Research Council*, 1932, p. 19.

C. K. Wentworth, "The Terminology of Coarse Sediments." *Bull.* 98, *Nat. Research Council*, 1935, p. 225.

V. T. Allen, "Terminology of Medium-grained Sediments." *Rep. Cmtee. on Sedimentation, Nat. Research Council*, 1935-1936, p. 18.

W. A. Tarr, "Terminology of the Chemical Siliceous Sediments." *Cmtee. on Sedimentation, Nat. Research Council*, 1936.

W. H. Twenhofel, "Terminology of the Fine-grained Mechanical Sediments." *Rep. Cmtee. on Sedimentation, Nat. Research Council*, 1936-1937, p. 81.

CLASSIFICATION OF SEDIMENTARY ROCKS.

GROUP CHARACTER.		TYPES.
A. Mechanical Origin	A1. Rudaceous	{ A1. 1. Conglomerate (p. 362).
		{ A1. 2. Breccia (p. 363).
	A2. Arenaceous	{ A2. 1. Sandstone (p. 366).
		{ A2. 2. Grit (p. 368).
		{ A2. 3. Arkose (p. 369).
		{ A2. 4. Quartzite (p. 370).
		{ A2. 5. Ganister (p. 371).
		{ A2. 6. "Greywacke" (p. 372).
		{ A2. 7. Siltstone (p. 373).
	A3. Argillaceous	{ A3. 1. Clay (p. 376).
		{ A3. 2. Fireclay (p. 378).
		{ A3. 3. Fuller's earth (p. 380).
		{ A3. 4. Æolian Clay (p. 381).
		{ A3. 5. Abyssal Clay (p. 382).
		{ A3. 6. Volcanic Clay (p. 383).
		{ A3. 7. Residual Clay (p. 384).
		{ A3. 8. Mudstone (p. 386).
		{ A3. 9. Shale (p. 386).
↓		
AB. Calcareo-Argillaceous	{ AB. 1. Marl (p. 388).	
	{ AB. 2. Calcareous Shale (p. 389).	
B. Organic Origin	B1. Calcareous	{ B1. 1. Limestone (p. 392).
		{ B1. 2. Dolomitic Limestone (p. 395).
		{ B1. 3. Oolitic and Pisolitic Limestone (p. 397).
		{ B1. 4. Abyssal Ooze (p. 398).
		{ B1. 5. Chalk (p. 399).
	B2. Siliceous	{ B2. 1. Chert and Flint (<i>in part</i>) (p. 401).
		{ B2. 2. Abyssal Ooze (p. 402).
		{ B2. 3. Siliceous Earth (p. 403).
	B3. Ferruginous	{ B3. Ferruginous Deposits (p. 405), see also under (C2) (p. 423).
	B4. Carbonaceous	{ B4. 1. Peat (p. 407).
		{ B4. 2. Lignite (p. 408).
		{ B4. 3. Coal and Anthracite (p. 409).
		{ B4. 4. Cannel and Torbanite (p. 412).
		{ B4. 5. Oil Shale (p. 413).
		{ B4. 6. Asphalt, Asphaltic Bitumen and Bituminous Impregnations (p. 414).
B5. Phosphatic	B5. Phosphate (p. 417).	

C. Chemical Origin	C1. Calcareous	{	C1. 1. Calcium Carbonate: Calcite (p. 421).
			C1. 2. Dolomite (<i>in part</i>) (p. 422).
	C2. Ferruginous	{	C2. 1. Bedded Iron-Ores (p. 423).
			C2. 2. Bog Iron-Ore (p. 425).
	C3. Siliceous		C3. 1. Siliceous Sinter (p. 426).
	C4. Saline	{	C4. 1. Chlorides (p. 427).
			C4. 2. Sulphates (p. 428).
			C4. 3. Nitrates and Borates (p. 430).

As in most branches of natural history, origin forms the soundest basis of classification and this starting point is almost universally adopted in the case of sedimentary rocks. Thus the primary division is:—

(A) MECHANICAL ORIGIN (p. 361).

(B) ORGANIC ORIGIN (p. 390).

(C) CHEMICAL ORIGIN (p. 419).

(A) Mechanical Origin

This implies the action of gravity and/or transport by wind, water or ice with subsequent deposition. The predominant character is initially incoherency, the individual particle varying from the ultra-microscopic or colloidal, to the largest boulder, subsequently (with the process of time) consolidation by various cementing media. Raw materials are essentially pre-existing rock-debris released during the normal progress of erosion. These are the “derived” or “allogenic” constituents (“allothigenous” of some authors). The cementing media, products of mineral destabilisation, organic or chemical agency, operate during or subsequent to the deposition phase; these are the “authigenic” constituents (“autothigenous” of some authors).

Rocks in this category may be subdivided into three groups on the basis of average grade-size, *i.e.* major dimension or diameter of predominant rock-fragment or particle (p. 85):—

(A1) RUDACEOUS (p. 362).

(A2) ARENACEOUS (p. 365).

(A3) ARGILLACEOUS (p. 374).

(A1) **Rudaceous Deposits.** — These include rocks composed of “granules,” “pebbles,” “cobbles” or “boulders” (p. 85) *i.e.* of materials exceeding 2 mm. in grade-size of predominant constituent. Talus and cliff debris, avalanche material (the “colluvial” deposits of G. P. Merrill), scree, shingle and gravel contribute the aggregates which, on consolidation, form either of two rock-types:—

(A1.1) Conglomerate (p. 362).

(A1.2) Breccia (p. 363).

(A1.1) **CONGLOMERATE.**

***Def.** A cemented clastic sediment composed of rounded fragments of pre-existing rock ranging in grade-size from pebbles to boulders (see p. 85).

Lith. Appearance of consolidated gravel. Bedding rare or absent. Colour variable, determined largely by matrix.

Text. Coarse. Matrix fine (cryptocrystalline), or sandy.

Shape. R to S.A. (ellipsoidal) pebbles.

Min. Comp. *Al.* Pebbles of quartz, quartzite, vein-quartz, chalcedonic silica, flint, chert; occasionally other rocks, *e.g.* limestone, including also igneous rocks. Accessory minerals scarce, usually absent from matrix, recoverable from pebbles by crushing.

Au. Silica, limonite, hematite; less commonly calcite, dolomite. Cement not only binds pebbles together, but sometimes penetrates cracks in them.

Mech. Comp. Minimum grade > 2 mm. Usual types 0.75-2.5 cm. Generally variable. (Matrix cryptocrystalline.)

Micro. Study relationship of pebbles to matrix; note boundary and whether both are in optical continuity (rare) or not; matrix normally fills interstices completely, especially in finer varieties. Quartz pebbles may be clear or turbid with inclusions: the latter are significant and may indicate origin (p. 492); undulose extinction due to strain sometimes noted. Chert generally exhibits aggregate polarisation; flint is usually cryptocrystalline or optically inert. Silica cement usually cryptocrystalline, but may be slightly coarser towards centre of interspace. Presence of calcite shown by “twinkling” and contrasted interference colour. White mica characteristic of some varieties. Presence of dolomite usually inferred from chemical test. Matrix

*** In order to abbreviate and systematise descriptions, rock-types are discussed under specific property “headings.”** *Def.*=short definition. *Lith.*=lithology, *i.e.* appearance to the naked eye, megascopic characters, macro-structure, colour etc. *Text.*=texture, either of whole rock if uniform, or of prominent components and matrix. *Shape* has reference to shape of predominant constituents expressed as R, rounded, SA, subangular, or A, angular. *Min. Comp.*=mineralogical composition, divided into *Al.*, allogenic and *Au.*, authigenic constituents. *Mech. Comp.*=mechanical composition (limiting grades for the type are given). *Micro.*=micro-structure as determined from microscopical study of thin sections. *Types*, usually of British origin, are cited to illustrate the rock under discussion; the selection has been specially made from accessible occurrences in order that the student, if he wishes, may collect or otherwise acquire such representative examples for study. Appropriate references (*Refs.*) are added.

may be contaminated with finer detritus, volcanic dust, also with minerals, *e.g.* pyrite, gold.

Types. Cambrian conglomerate of quartz, quartzite, felsite, schist, granite etc., of Pre-Cambrian origin in siliceous and ashy matrix, St. Davids, South Wales;¹ the Bunter Pebble Bed, with chocolate-coloured quartzite, Carboniferous Limestone, purple grit and volcanic rocks in siliceous or calcareous matrix, Midland counties;² "Dolomitic Conglomerate," chiefly Carboniferous Limestone pebbles from 2 in. up to boulders, 3 ft. in diameter, set in a calcareo-dolomitic cement, of the Mendip and Bristol area (Trias);³ Eocene "pudding stone" of Hertfordshire and Kent, mostly quartz pebbles in crypto-crystalline, siliceous matrix (Fig. 84).⁴

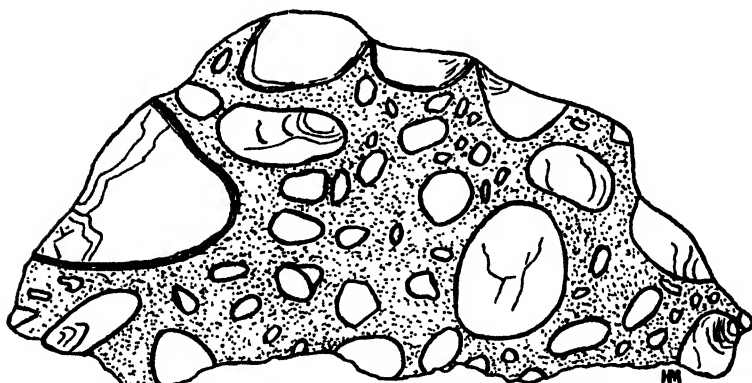


FIG. 84. Drawing of smooth surface of Flint Conglomerate (Hertfordshire "Pudding Stone"). [$\frac{1}{3}$ Nat. Size.]

Refs. ¹ H. Hicks, *Quart. Journ. Geol. Soc.*, 27, 1871, p. 386.

² T. G. Bonney, *Quart. Journ. Geol. Soc.*, 56, 1900, p. 287.

³ A. J. Jukes-Browne, "Stratigraphical Geology." (Stanford, London), 1912, p. 366.

⁴ J. Hopkinson, *Geol. Assoc. Jubilee Vol.*, 1910, p. 16.

General Refs.

J. W. Gregory, *Geol. Mag.*, 1915, p. 447.

R. M. Field, "A preliminary paper on the origin and classification of intraformational conglomerates and breccias." *Ottawa Nat.* 30, 1916, p. 29, 47, 58.

A. Hadding, "The pre-Quaternary Sedimentary Rocks of Sweden." II "The Palæozoic and Mesozoic Conglomerates of Sweden." *Lunds Univ. Arsskrift*, 23, 1927, p. 42.

W. H. Twenhofel, "Treatise on Sedimentation." (Ballière, Tindall and Cox, London), 1932, p. 201.

(A1. a) **BRECCIA.**

Def. A clastic sediment comprising angular pre-existing rock fragments, usually of varied composition and grade-size, cemented by siliceous, calcareous or other secondary medium.

Lith. Rock-fragments of distinctive shape and miscellaneous size set in a matrix of mixed character and composition. Fragments may be of the same rock or dissimilar according to uniformity or variation of

parent-rocks. Bedding rare. W. H. Norton¹ recognises four megascopic types:—“*crackle breccia*,” representing incipient brecciation, with fragments parted by fission-planes, but subject to little or no displacement; such fragments “match” along their opposed sides; matrix confined to interstices and is usually of chemical origin. The “*mosaic*” type has its fragments largely disjointed and displaced. “*Rubble breccia*” exemplifies the type “in which no matching fragments are parted by initial planes of rupture. The fragments are close-set and in touch.” The “*breccia of sporadic fragments*” is the type in which the matrix preponderates over fragments which are “like plums in a pudding.” Where the matrix is bedded, the breccia belongs to the “*endostratic*” type, of which some of the Permian “*breccia sandstones*” are examples.² In the fossiliferous breccias, fossils may occur both in fragments and in matrix, but usually the latter. Contemporaneous brecciation with deposition gives rise to “*intraformational breccias*” (C. D. Walcott).

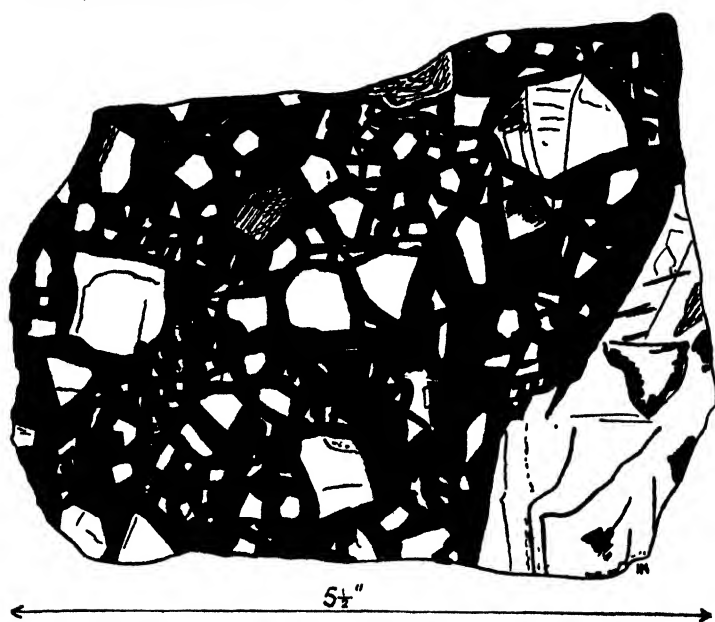


FIG. 85. Breccia with calcite fragments etc.

Text. Coarse, determined by the size of the fragments. Matrix usually fine, like mud, or gritty.

Shape. A. Fragments sometimes show signs of attrition acquired during local transport. Particles in matrix both A and SA.

Min. Comp. Al. Any rock-type is likely to contribute, given the requisite conditions; even the softest rocks may, as fragments, survive in breccias in which little or no transport has been involved.

¹ W. H. Norton, *Journ. Geol.*, 25, 1917, p. 161.

² W. King, *Quart. Journ. Geol. Soc.*, 55, 1928, p. 97.

Au. Matrix may be composed of pulverised rocks represented as fragments, or may be of different origin; fine silt or mud; chemical deposit, e.g. calcite, limonite. Usually very mixed in composition.

Mech. Comp. Minimum grade >2 mm. Usual types 0.5-3.0 cm., maximum length of fragment; but much larger fragments may occur, even huge blocks weighing several tons each. Matrix composed of particles <0.01 mm. in the finest muddy types, ranging up to 1 mm. in the gritty types.

Micro. Study relationship of fragments to matrix; note boundaries and extent to which matrix forms seams or fills interspaces. Proportion of matrix to fragments important; in some types the latter predominate, in others the matrix is more conspicuous than the fragments (see Fig. 85). Diagnose coarse constituents and note variety of rock-types represented; if one predominating type is found, note to what extent its characteristic minerals have contributed to the matrix. Composite or simple character of the fragments also important. Examine matrix for rock-particles and individual minerals, also for alteration products and special cementing media of chemical origin. Cementing materials, where contaminated with rock-powder, usually require long and careful scrutiny to establish complete diagnosis. Shell-fragments noted in fossiliferous varieties.

Types. Permian breccias in the Penrith Sandstone, Eden Valley, Cumberland etc., "The Brockrams"; one type (lower) is made up of Carboniferous Limestone fragments in a red sandy matrix; the other (upper) contains fragments of basal Carboniferous conglomerate reinforced by Ordovician rocks, vein-quartz etc.¹ Upper Permian breccias of the Midlands, "Trappoid Breccias," in which the fragments are mainly of volcanic origin (old field-term "trap"), with quartzites, sandstone and limestone of Pre-Cambrian, Cambrian, Ordovician and Silurian origin.² Pleistocene breccias, Severn Estuary.³

Refs. ¹ A. J. Jukes-Browne, "Stratigraphical Geology." (Stanford, London), 1912, p. 337.

² W. W. King, *op. cit.*

³ L. S. Palmer, *Proc. Geol. Assoc.*, 45, 1934, p. 145.

General Refs.

W. H. Norton, *Journ. Geol.*, 35, 1917, p. 161.

S. H. Reynolds, *Geol. Mag.*, 65, 1928, p. 97.

(A2) Arenaceous Deposits. — These are the true clastic accumulations and include sands, sandstones, silts etc., the predominant constituents of which fall between the size-limits 0.01 and 2 mm. (p. 85); the conventional silt grade-limits are 0.1-0.01 mm.; the consolidated form, siltstone, is sometimes separated as a distinct group.¹ Since, however, this constitutes a specific rock-type rather than a group comparable in importance with other mechanically-formed deposits (A₁, A₃), it is here classified under arenaceous deposits. The raw materials are essentially sand, rainwash etc., and these on consolidation give rise to the following types:—

¹ G. W. Tyrrell, "Principles of Petrology." (Methuen, London), 1926.

- (A2. 1) Sandstone (p. 366).
- (A2. 2) Grit (p. 368).
- (A2. 3) Arkose (p. 369).
- (A2. 4) Quartzite (p. 370).
- (A2. 5) Ganister (p. 371).
- (A2. 6) "Greywacke" (p. 372).
- (A2. 7) Siltstone (p. 373).

(A2. 1) **SANDSTONE.**

[Pl. 32 A, B, D, facing p. 368.]

Def. An arenaceous rock composed substantially of detrital quartz grains, subangular to rounded in shape, ranging from 0.1-2 mm. in grade size and cemented with siliceous, calcareous, ferruginous or other authigenic medium.

Lith. Compounded essentially of derived quartz grains cemented by a matrix which may or may not be conspicuous. Predominantly siliceous, the purest varieties containing over 99.5 per cent. SiO_2 . Bedding usually apparent, thin (laminæ) or thick, either regular, horizontal, or current- or cross-bedded. Colour determined largely by nature of cementing medium, the commonest being limonite (brown), hematite (red); highly siliceous types are white to colourless. Organic components common, often casts. Structural features include ripple-marks, veining, cross-joints, organic markings, rain-prints, sun-cracks etc.

Text. Coarse (0.5-2 mm.), medium (0.25-0.5 mm.), and fine (0.1-0.25 mm.).

Shape. Generally SA (water-worn grains); R in wind-blown sand; A in glacial sand. Predominantly angular in Grit, A2. 2.

Min. Comp. Al. Quartz, muscovite, feldspar (see under Arkose, A2. 3, p. 369); occasionally rock-particles of igneous or volcanic origin; accessory minerals such as ilmenite, magnetite, zircon, tourmaline, garnet, rutile etc.

Au. Cementing materials include siliceous, ferruginous, calcareous, argillaceous and carbonaceous matter, in that order of normal occurrence. More rarely barite.

Mech. Comp. Size-limits are 0.1-2 mm. ("sand grade"); average about 0.2 mm. If the sand is superfine (=coarse silt) the lower limit is 0.05 mm.

Micro. Study quartz grains for shape, grading (uniform or mixed), degree of preservation of crystallisation (euhedrism), inclusions (p. 332) and optical character, i.e. whether normal or undulose extinction. Muscovite detected by its irregular flaky character, cleavage and interference colours (pinks, greens and yellows). Other prominent constituents, e.g. glauconite, should present no difficulty; accessory minerals best investigated by crushing and concentration (p. 80). Quartz grains may be mutually interferent, with little or no cementing matter, when the rock approximates to the quartzite type (A2. 4); in most examples the matrix is clearly discernible and limonite, hematite, calcite, silica etc., will be easily determined. Differentiate between types in which each quartz grain is completely surrounded by cement; in which grains occur in clusters, many touching, the cement being haphazardly distributed; and those in which there is apparently more cement than derived matter. Relation of grains to cementing medium, especially peripheral contact, is important. Secondary outgrowths of silica from original quartz nuclei, each outgrowth being

in optical continuity with its nucleus, are sometimes observed. Siliceous cement may be cryptocrystalline or microcrystalline. It is seldom that only one material constitutes the cement; calcite is detected by "twinkling," hematite and limonite by colour, likewise carbon. Calcareous cement may be anticipated where organisms prevail. Greenish cement is not necessarily due to glauconite, but more often to chloritic matter after ferromagnesian minerals. Clayey matter gives rise to a dirty brown, almost indecipherable cement, though usually micaceous. Gypsum, barite, dolomite, are uncommon authigenic constituents, but are not hard to identify.

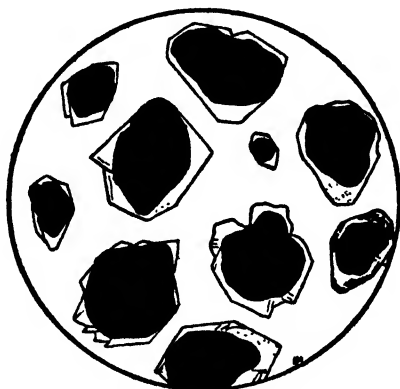


FIG. 86. Grains from the Penrith Sandstone (Permian), Cumberland, showing secondary outgrowths of quartz. [x 25.]

Types. Hollybush Sandstone (Cambrian) of Malvern etc., a mica-glauconite-bearing rock;¹ Bala Sandstone of the Welsh Borders (Ordovician), a ferruginous, micaceous type with many shell-casts; Old Red Sandstone, Herefordshire and South Wales, with hematite cement;² Permian Sandstone, Penrith, Cumberland (Fig. 86), with beautiful crystal outgrowths in optical continuity with nuclei (desert sand);³ Triassic Sandstone, Alderley Edge, Cheshire, with barite cement and impregnations of azurite, malachite, galena etc.;⁴ Ash-down Sand (Wealden), Fairlight, Sussex, pure white "glass" sandstone;⁵ Lower Greensand, Faringdon, Berkshire, with glauconite, sponge remains and calcite "platy" cement enveloping sand grains in "ophitic" fashion;⁶ Lower Greensand, Ightham, Kent ("Ightham Stone"), with radial, chalcedonic cement enclosing grains;⁷ Lower Greensand ("Carstone"), Hunstanton, Norfolk and Yorkshire, with heavy ferruginous cement and oolitic grains of iron-ore with siliceous skeleton (on treatment with acid);⁸ Upper Greensand, Sutton Poyntz, Dorset, glauconitic sandstone (glauconite casts of *foraminifera*) with siliceous and calcareous cement;⁹ Eocene Sandstone ("Sarsens"), chalk downs of Wiltshire, Dorset etc., fine micaceous rock graduating to quartzite type;¹⁰ Bagshot Sand, Studland etc., Dorset, deep reddish-brown, ferruginous sandstone and variegated types.¹¹

Refs. ¹ G. S. Sweeting, *Proc. Geol. Assoc.*, 38, 1927, p. 552.

² A. Heard and R. Davies, *Quart. Journ. Geol. Soc.*, 80, 1924, p. 489.

- ³ A. Harker, "Petrology for Students." (University Press, Cambridge), 1919, p. 212 and *Fig. 72, F.*
- ⁴ J. W. Judd, *Quart. Journ. Geol. Soc.*, 40, 1884, p. 749.
- ⁵ P. G. H. Boswell, "British Resources of Sands for Glass-Making." (Longmans, Green, London), 1918, p. 52.
- ⁶ Author's observations.
- ⁷ T. G. Bonney, *Geol. Mag.*, 1888, p. 297.
- ⁸ H. C. Versey and C. Carter, *Proc. Yorks. Geol. Soc.*, 20, 1926, p. 349; also A. Harker, *op. cit.*, p. 212.
- ⁹ Author's observations.
- ¹⁰ H. B. Woodward, *Geol. Assoc. Jubilee Vol.*, 1910, p. 304.
For Upper Cretaceous sandstones of England, see W. Hill, *Mem. Geol. Surv., Cret. Rocks Brit.*, vol. i, 1900, ch. xxv.
- ¹¹ Author's observations.

General Refs.

- L. Cayeux, "Structure et Origine des Grès du Tertiaire parisien." (Masson, Paris), 1907.
 "Les roches sédimentaires de France: Roches Siliceuses." *Mem. pour servir à l'explication de la carte géologique détaillée de la France*, Paris, 1929.
 A. Hadding, "The pre-Quaternary Sedimentary Rocks of Sweden. III Palæozoic and Mesozoic Sandstones of Sweden." *Lunds Univ. Årsskrift*, 25, 1929.
 W. H. Twenhofel, "Treatise on Sedimentation." 1932, p. 218.

(A2. 3) GRIT.

[Pl. 32 C, E, F, facing p. 368.]

Def. Restricted to an arenaceous rock composed substantially of detrital quartz grains of predominantly angular shape, ranging from 0.1-2 mm. in grade size and cemented with siliceous, calcareous, ferruginous or other authigenic medium.

Lith. The separation of this type from normal sandstone depends on the angularity of the quartz particles, a feature not always apparent from megascopic examination. Every gradation from grits, in which the particles are equidimensional, through pebble-grits, to conglomerates (A1. 1) is met with. In the coarse varieties prominent constituents are identifiable with the naked eye (chiefly quartz, quartzite). Stratification normally developed on a large scale and may not be apparent in the hand-specimen. Colour variable but usually yellow, buff, brown or grey. Organic remains may be present in the medium and fine varieties, less frequently in the coarse types. Prominent pebbles should be extracted and dealt with separately.

Text. Coarse to medium.

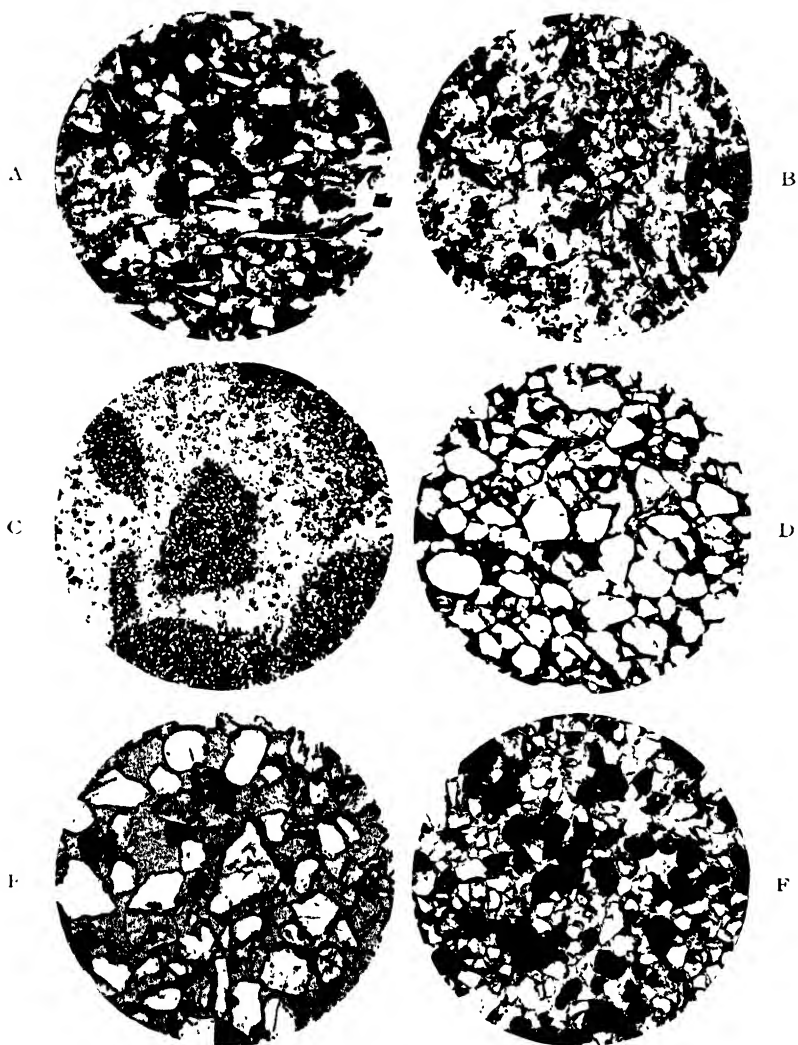
Shape. A.

Min. Comp. Al. Quartz; composite grains of quartz and feldspar, muscovite, particles of igneous, volcanic and metamorphic origin; also of the harder sedimentary rock-types; quartzite; vein-quartz. Stable accessory "heavy" minerals.

Au. Siliceous, calcareous, ferruginous and argillaceous cements; the first two materials are commonest. Micaceous and chloritic matter often prevalent.

Mech. Comp. Size-limits of derived particles in true grits fall between 0.1-2 mm. Above the latter grade the rock passes into a fine conglomerate (*q.v.*). Many types described as grits are mechanically classifiable under the latter heading, especially when pebbles occur.

Micro. Microscopic examination reveals at once the angularity of the predominant grains, though some degree of rounding is nearly always



SANDSTONE AND GRIT.

- A. Hollybush Sandstone (Cambrian), Malvern [x 30.]
- B. May Hill Sandstone (Silurian), Malvern. [x 30.]
- C. "Tilgate Stone," Calcareous Grit (Wealden), Sussex [x 25.]
- D. Ferruginous Sandstone (Aptian), Betchworth, Surrey [x 15.]
- E. Calcareous Grit (Aptian), Faringdon, Berks. [x 25.]
- F. Glauconitic Grit (Selbornian), Sutton Poyntz, Dorset. [x 15.]

apparent. Inclusions in the quartz grains noteworthy. Most examples show mixed composition and present interesting problems in the identification of components. In certain calcareous grits "lustre-mottling" is a striking feature, sometimes seen in the hand-specimen, but more conspicuous in thin section. "When the polariser is in position . . . the differential relief ('twinkling' effect) characteristic of the rhombohedral carbonates resolves the field into areas within each of which the calcite cementing the quartz grains is in crystallographic continuity . . . lustre-mottling . . . is due to the reflection of light from the calcite cleavages which are differently orientated."⁶ Other points in diagnosis as for Sandstones (*q.v.* p. 366).

Types. Ingletonian Grit of Yorkshire, with grains of gneiss, lava etc., in addition to quartz, feldspar, mica;¹ Watch Hill Grit (Bala) of Cumberland, with vein-quartz, carbonaceous shale, spilosite, composite quartz-feldspar fragments, schist and granophyre (from Carrock Fell complex) with quartzose, feldspathic, micaceous and silty matrix;² Staddon Grits (Devonian) of South Devonshire etc., purplish-red, with siliceous and calcareous cements;³ Millstone Grit of Yorkshire, notable specially for quartz inclusions, pebbles and accessory minerals;⁴ Inferior Oolite ("Moor Grit"), Yorkshire, tending to quartzite type;⁵ "Tilgate Stone" (calcareous grit with "lustre-mottling"), Wadhurst Clay (Wealden), Sussex.⁶

Refs. ¹ R. H. Rastall, *Proc. Yorks. Geol. Soc.*, 16, 1906, p. 94.

² J. F. N. Green, *Proc. Geol. Assoc.*, 28, 1917, p. 21.

³ W. G. Shannon, *Proc. Geol. Assoc.*, 39, 1928, p. 144.

⁴ A. Gilligan, *Quart. Journ. Geol. Soc.*, 75, 1919, p. 251.

⁵ A. Harker, "Petrology for Students." (University Press, Cambridge), 1919, p. 210.

⁶ G. S. Sweeting, *Proc. Geol. Assoc.*, 36, 1925, p. 413.

N.B.—"Pea Grit," "Trigonia Grit" etc., are not true grits (p. 397).

(A2. 3) **ARKOSE.**

[Pl. 33 A, facing p. 372.]

Def. A sandstone or grit in which detrital feldspar is a permanent constituent (25 per cent. or more). Implies derivation from granite, gneiss etc., containing abundant feldspar.

Lith. Comparable with either sandstone or grit, generally the latter. A type separated to designate a feldspathic sandstone or grit derived from granitoid or gneissic rocks and containing prolific feldspar, the latter usually only determinable under the microscope. Colour often pale red or purple, but may vary. White mica usually prominent.

Text. Coarse to medium.

Shape. A to SA.

Min. Comp. Al. Quartz, feldspar (microcline, orthoclase, plagioclase, micropertite etc.), muscovite; rock-fragments of miscellaneous origin; iron-ores and stable accessory minerals.

Au. Siliceous, calcareous, feldspathic, hematite and limonite; greenish colour due to chlorite minerals and/or epidote; occasionally carbonaceous.

Mech. Comp. As for sandstone and grit (*q.v.*).

Micro. The chief study in these rocks is the feldspar, of which microcline and oligoclase appear to be the commonest constituents. Note relative proportions of quartz and feldspar grains. Determine carefully the optical properties of the feldspars present. Much of the quartz may show strain-polarisation effects. Quartz and feldspar grains may be in mutually interferent aggregates surrounded by cementing medium, or each grain may be enveloped in a thin film of iron oxide; in the less

coloured varieties, silica and/or calcite cement is common. Arkoses generally approximate to the quartzite type (A2. 4) and are highly siliceous. Nature and degree of distribution of derived grains in cement important and diagnostic. Other criteria as for sandstone, grit.

Types. Torridonian rocks of the N.W. Highlands, with various feldspars, distinctive quartz and pebbles of more ancient rocks;¹ Millstone Grit of Yorkshire.²

Refs. ¹ J. L. H. Teall, "Geology of the N.W. Highlands." *Mem. Geol. Surv. Great Britain*, 1907, ch. xvi (an excellent and exhaustive account of this rock-type).

² A. Gilligan, *Quart. Journ. Geol. Soc.*, 75, 1919, p. 251.

General Ref.

D. C. Barton, *Journ. Geol.*, 24, 1916, p. 417.

A. Hadding, "The pre-Quaternary Sedimentary Rocks of Sweden. II Palaeozoic and Mesozoic Sandstones of Sweden." *Lunds Univ. Arsskrift*, 25, 1929, p. 151. (Account of the *sparagmites* of Scandinavia.)

R. D. Reed, "Geology of California, Tulsa, Oklahoma." *Amer. Assoc. Petrol. Geol.*, 1933.

(A2. 4) **QUARTZITE.**

[Pl. 33 B, C, D, facing p. 372.]

Def. A normal sandstone or grit in which the detrital quartz is cemented by secondary silica, often in optical continuity; or a metamorphosed, recrystallised sandstone composed essentially of quartz.

Lith. Distinguish from quartzite of metamorphic origin. The sedimentary type consists almost exclusively of quartz grains set in a siliceous cement. Normally a pale-coloured, close-grained or "sugary" rock of obvious siliceous character. Impurities may be rock-fragments visible to the naked eye, ferruginous matter, mica etc. Quartz is often water-clear. Bedding generally only apparent on a large scale. Organisms not common.

Text. Coarse to medium; in special types, very fine (*cf.* A2. 1, p. 371).

Shape. SA.

Min. Comp. Al. Quartz, subordinate feldspar, mica, few accessory minerals.

Au. Silica, sometimes with finely disseminated iron oxide; less commonly carbonaceous and silty matter.

Mech. Comp. Average of many examples shows detrital grains of grade-size 0.2–0.3 mm., *i.e.* of medium grade.

Micro. Under the microscope quartzites present characteristic mosaic, often granular appearance, the quartz grains closely set in a clear siliceous cement; with passage of the rock to less pure sandstone, the grains tend to be more scattered and the cement more prominent. In some examples the cementing medium develops directly from detrital nuclei by crystalline outgrowths, sometimes in optical continuity. Occasionally cement is clouded by finely divided silty matter or dust; calcite not common. White mica prevalent and, in certain cases, feldspar in sufficient quantity to designate the rock an arkose. Note particularly the size and shape of the quartz grains, any inclusions, unusual optical properties, also the relationship of grains to matrix. Distinguish sedimentary quartzite from metamorphosed sandstone by the fact that in the latter there is practically no differentiation of detrital grains and matrix, the whole being a homogeneous quartzose rock of mutually interferent quartz pellicles.

Types. Pre-Cambrian quartzite, Islay, Jura etc., Argyllshire, fine-grained saccharoidal type;¹ Dalradian Quartzite (Pre-Cambrian), Kentallen, Argyllshire, with little micropertite, pyrite and a minimum of siliceous cement;² Appin Quartzite from same region, similar;³ Harts-hill Quartzite (Pre-Cambrian) of Warwickshire, a pinkish compact type with somewhat worn quartz grains, a little felspar, chloritic matter and epidote after ferromagnesian minerals, also siliceous cement, in many cases recrystallised about detrital grains;³ Stiper-stones Quartzite (Ordovician), Shropshire, with mica and silty siliceous cement;⁴ Estuarine quartzites, Comondale, Glaisdale, Castle-ton etc., Yorkshire, compact types with cryptocrystalline ground-mass.⁶ See also under "Ganister" (A2. s, below).

Ref. ¹ H. H. Thomas, *Mem. Geol. Surv., Spec. Rep. Min. Resources Great Britain*, 16, 1920, p. 13.

² Author's observations.

³ W. W. Watts, *Summ. of Progress Geol. Surv. Great Britain*, 1897, p. 68, and *Proc. Geol. Assoc.*, 15, 1898, p. 393, 397.

⁴ A. Harker, "Petrology for Students." (University Press, Cambridge), 1919, p. 209, 214.

⁵ H. H. Thomas, *op. cit.*, p. 13, pl. 2, Fig. 3.

General Ref.

W. J. Sollas, *Sci. Proc. Roy. Dublin Soc.*, 7, 1892, p. 169.

(A2. s) GANISTER.

[Pl. 33 E, facing p. 372.]

Def. A hard, compact, highly siliceous sedimentary rock, with fine, uniform, granular texture and composed essentially of angular quartz grains cemented with secondary silica.

Lith. In its strict interpretation ganister is a particular kind of highly siliceous rock, a variety of quartzite, comparable with the "Sheffield Ganister," a well-known refractory material occurring in the Ganister group of the Lower Coal Measures. There are many varieties, from the pure quartzose rock to the less pure "bastard ganister" and "silica rock." Ganister is hard, compact, uniform in texture, and of a blue-grey, buff or white in colour, often streaked with carbonaceous rootlets. Bedding seldom observed on a small scale. Fracture is characteristic, yielding smooth, subconchoidal hollows; newly broken edges very sharp. Some types have the appearance of "horn-stone." Dark coloured types usually denote considerable impurity and are seldom true ganisters.

"In its typical form ganister is distinguished from flint and chert by its more granular texture and by the relatively small quantity of chalcedonic or amorphous silica." . . . "Bastard ganister" has been applied to a group of silica rocks which present many of the superficial characters of the true ganister, such as colour and the impressions of rootlets, but differ in certain essential details, namely in the increased amount of interstitial matter, the greater variability of texture, and often in a relatively incomplete silicification. It has become a practice to call other sandstones and quartzites which are capable of employment for silica brickmaking 'silica rock' to distinguish them from true ganisters." (See *General Ref.*)

Text. Homogeneous, compact, fine-grained; sometimes granular or saccharoidal.

Shape. SA.

Min. Comp. AL. Quartz, chert, orthoclase, felspar and stable accessory minerals, e.g. iron-ores, tourmaline, rutile, anatase, titanite, zircon.

AU. Silica, hematite, limonite, kaolinite, sericitic mica, clayey matter.

Mech. Comp. Average grade-size 0.05 mm.-0.15 mm. Coarser types up to 0.5 mm. Sometimes very small interstitial grains 0.02 mm. observed. Extremely coarse types show passage into normal grits.

Micro. Normal rock consists of a mosaic of angular quartz grains often remarkably uniform in shape and size. These may be closely packed, giving rise to an interlocking structure, or siliceous cement may be conspicuous in places. This cement is usually cryptocrystalline, often chalcedonic. Where grains vary in size, the smaller pack together between the larger. Finely divided carbonaceous dust frequently permeates the rock. A network of veins usually traverses the rock, filled with silica, limonite, carbon, rarely with calcite.

Types. Lower Coal Measures. Sheffield Ganister ("Hard Mine"), the type rock; another variety from Deepcar is saccharoidal and streaked with carbonaceous matter;¹ another from Huddersfield contains abundant mica and rutile; the Hawksworth Ganister ("Guiseley Rock") is a very pure type;² Lower Coal Measures, ganister, of Wingfield Park, Ambergate; also Wessington area, Derbyshire.³

Refs. ¹ *Mem. Geol. Surv. Spec. Rep. Min. Resources Great Britain*, 6, 1918, p. 23.

² *Op. cit.*, p. 32.

³ Author's observations.

General Ref.

For general account of ganister, silica rocks etc., see H. H. Thomas, *Mem. Geol. Surv., Spec. Rep. Min. Resources Great Britain*, 6, 1918, and 16, 1920.

(A2. *) GREYWACKE (Grauwacke, Graywacke).

[Pl. 33 F, facing p. 372.]

Def. "A sandstone composed of 33 or more per cent. of easily destroyed minerals and rock fragments derived by rapid disintegration of basic igneous rocks, slates and dark coloured rocks. It may or may not be intensely indurated or metamorphosed" (V. T. Allen).

Lith. An old field-term which has been usefully revived to designate arenaceous rocks of a peculiar type, specially developed in British palaeozoic formations. Essentially a sandstone compounded of quartz and miscellaneous rock-particles of diverse origin, the latter often in excess of the detrital quartz. The very mixed character of these rocks is usually discernible at a glance, while the grey, green or darker colour is common. Often highly micaceous, well bedded, usually void of recognisable organic remains.

Text. Coarse to medium, "gritty."

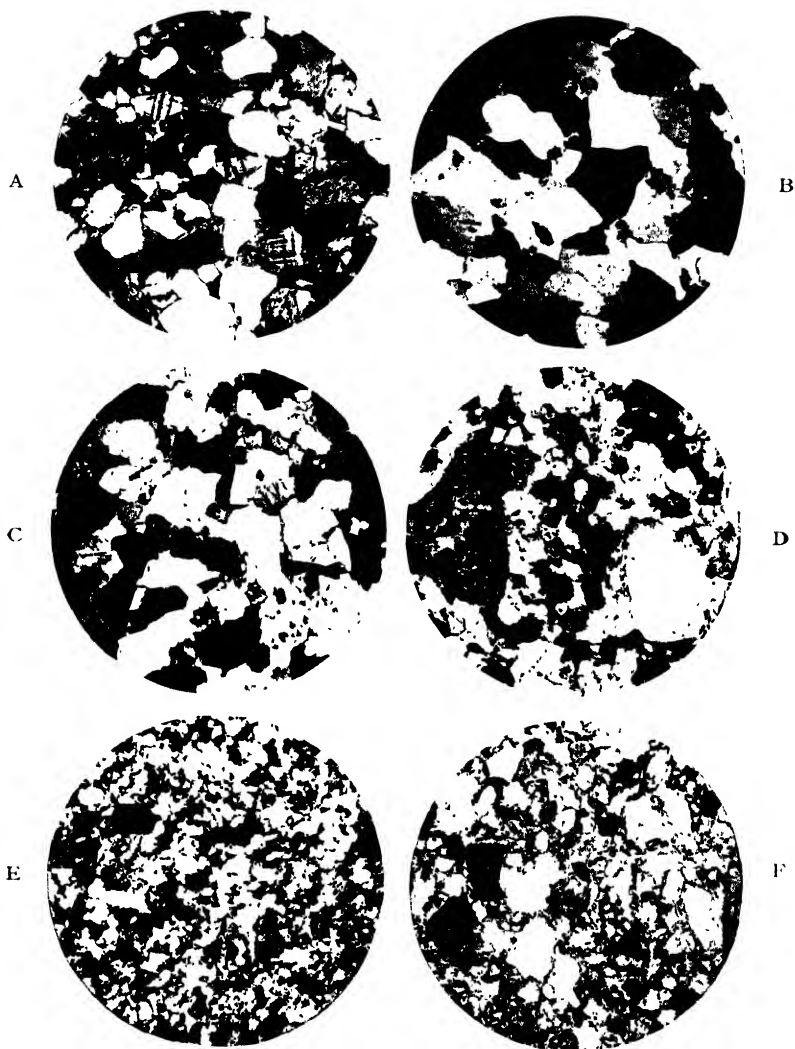
Shape. A.

Min. Comp. Al. Rock-particles include fragments of basic rocks, slates, sandstones and volcanic lavas. Quartz, chert, quartzite, mica, iron-ores and usually scanty accessory minerals.

Au. Silica, ferruginous, chloritic and argillaceous matter.

Mech. Comp. Variable from sand-grade to much coarser material (rudaceous).

Micro. The microscopic study of these rocks is somewhat similar to that of breccias, only on a much smaller scale. The student has to be prepared for practically any rock-type in the form of small or large grains or flakes and a knowledge of the locality and geologic history of the rock under investigation helps considerably in determining the nature of the derived fragments present. Quartz presents no difficulties by itself, but the cementing material, being often packed full of fine rock-dust, is difficult of identification. Usually decomposition products such as mica, chloritic matter, kaolinite and/or epidote, are



ARKOSE, QUARTZITE AND GREYWACKE.

- A. Torridon Sandstone (Arkose), Loch Torridon, Ross * [x 25.]
 B. Quartzite (Archaean), Kentallen, Argyllshire.³ [x 18.]
 C. Hartshill Quartzite (Cambrian), Nuneaton.* [x 18]
 D. Malvern Quartzite (Cambrian), Gullet Pass, Malvern. [x 25]
 E. Gaisler (Coal Measures), Sheffield, Yorks * [x 25]
 F. "Greywacke" (? Carboniferous), Richmond Boring, London (1150 ft).
 [x 25]

[*Crossed Nicols.]

conspicuous. These rocks are for the most part structureless and exhibit a heterogeneous constitution of marked variation from one example to another.

Types. Ordovician "greywacke" of Montgomeryshire, with abundant volcanic inclusions; Old Red Sandstone, Welsh Borders, purplish-grey, brown and greenish types with plutonic, volcanic and sedimentary rock-particles.¹

Refs. ¹ G. W. W. Tyrrell, "Principles of Petrology." (Methuen, London), 1926, p. 209.

General Refs.

G. W. Tyrrell, "Greenstones and Greywackes." *C.R. Réunion Inter. l'étude Pre-Cambrian etc.*, Bull. Geol. Comité. Finland, 102, 1933, p. 24.

G. Fischer, "Die Petrographie der Grauwacken." *Jahr. Preussischen Geol. Landenstat*, 54, 1933, p. 320.

V. T. Allen, "Terminology of Medium-grained Sediments." *Rep. Comité. Sedimentation*, Nat. Research Council, 1936, p. 28, 46.

(Az. 1) SILTSTONE.

Def. A fine-grained arenaceous rock whose detrital particles are predominantly of the silt grade, i.e. 0.01-0.1 mm.

Lith. This type has been separated by J. F. N. Green¹ to comprise those rocks which are essentially compacted silts, conforming in grade to the latter raw material (p. 85). They are principally products of fluvial, lacustrine, glacial and æolian action, in other circumstances of volcanic origin and usually present distinctive features. The fine sandy character is typical, together with perfect lamination in the aqueous types. Such lamination may be picked out by different coloured iron-oxide films, depending on the degree of impregnation developed from plane to plane. Fine current-bedding and ripple-marking are also observed in some types. Organic remains are common, especially carbonaceous plant-fragments. Colour normally grey, buff or brown except in the æolian types, when hematite staining may be prominent. Siltstones frequently illustrate the phenomenon of rhythmic banding, especially those of lacustrine origin.

Text. Essentially fine textured, close grained and compact; some varieties earthy.

Shape. SA in all except æolian types, the latter SA to R.

Min. Comp. Al. Quartz, muscovite, felspar, iron-ores and miscellaneous accessory minerals. Siltstones as a rule yield a fair quantity of heavy residue.

Au. Siliceous, ferruginous and calcareous cement; carbonaceous dust often present. Much of the irresolvable matter is clay.

Mech. Comp. Particles fall between the size-limits 0.01 mm. and 0.1 mm. Average about 0.06 mm.

Micro. In finely laminated varieties study by means of sections cut both parallel and transverse to lamination. The former exhibits a mass of fine quartz particles with cementing matter enveloping each, or clustered aggregates giving a patchy mosaic structure; this type of section should also show the relationship of the matrix to the detrital particles, the character of any organisms present and especially the development of mica. The transverse section exhibits some degree of parallelism of the component minerals, variations in these from plane to plane and longitudinal sections of any organisms present, i.e. those reposing normally with the bedding. In many examples the manner of impregnation of the authigenic matter is best studied from

¹ See *Ref.* ¹ p. 374.

these transverse sections. Much of the cement, if argillaceous, may be difficult to decipher and may also prove optically inert, owing to its extreme finely divided state (see A3, below). Miscellaneous rock-particles, composite or simple in character, prevail in some examples, thus allying the type with the "greywackes" (A2. 4, p. 372). The presence of calcite is frequent and is usually easily detected.

Types. Silurian of North Wales; also Lake District;¹ Old Red Sandstone, Caithness, N.B., slaty "flagstones" with abundant lime and organic matter;² Keuper silts and marls, Leicestershire;³ Ashdown Sand (Wealden), Sussex, siltstones of fluviatile origin, finely laminated, ferruginous cement, with plant remains, ostracods etc.;⁴ Weald Clay siltstone (Wealden), Horsham, Sussex, with calcareous cement, lignite etc.⁵

Refs. ¹ J. F. N. Green, in A. Holmes, "Nomenclature of Petrology." 2nd ed. (Murby, London), 1929. "Siltstone," p. 21.

² *Mem. Geol. Surv. Scotland*, "Geology of Caithness." 1914, p. 89.

^{3, 4, 5} Author's observations.

(A3) Argillaceous Deposits.—This division comprises all the finest mechanically-formed sediments, represented essentially by clays and those rock-types produced therefrom by consolidation and by expression of moisture. The constituent particles range from an upper limit of 0.01 mm. in diameter to ultra-microscopic and colloidal matter. Of all sediments these are the most difficult to investigate thoroughly from a petrological standpoint, owing to the finely divided state of their components and also because of the difficulty of determining by ordinary methods much of the authigenic matter which as "clay paste" defies diagnosis by petrological means alone. The intensive use of improved optical, X-ray and base exchange studies of clay minerals has, however, provided a most valuable technique for investigating these finely divided materials; much that has hitherto defied interpretation is gradually being made clear by progressive research along these lines (See also Chapter XIV, p. 524 *et seq.*).

Recent work has shown that at all events kaolinite does not play the supreme part in constitution of these rocks as formerly imagined; only in certain restricted types is this mineral really prevalent. Much of the modern work on soils, also on clays employed in the ceramic industry, has thrown a flood of light on the real composition of argillaceous rocks and the recognition of the nature and role of the "colloidal complex," mostly attributable to various hydrated aluminous silicates, is a definite step towards their better understand-

ing. In another direction, chemical and physical analyses of various clays suited to particular purposes in the arts, has led to certain definite conclusions on mineralogical composition. The work of C. S. Ross and E. V. Shannon on bentonite,¹ for instance, was a distinct advance and an inspiration to similar research on other types of clay, hence on the consolidated rocks to which it gives rise. This will be referred to again in what follows.

Several attempts have been made in the past to bring the varied clay types within a comprehensive scheme of classification, especially in America; such classifications have depended either upon origin, chemical analysis, physical properties or on their behaviour under conditions of heat or desiccation. As with attempts at mineralogical classification of clays, none of these has yet succeeded in bringing within a convenient compass all varieties known, or in framing a logical scheme as a basis of petrological analysis and description. Thus, although argillaceous rocks in general and clays in particular, enjoy a literature far surpassing in bulk that available in connexion with any other sediments, descriptions are still in most cases arbitrary and biassed according to the particular angle from which the writer happens to view the subject: witness the classifications enunciated by E. Orton,² H. A. Wheeler,³ G. E. Ladd,⁴ E. R. Buckley,⁵ G. P. Grimsley and F. F. Grout,⁶ H. Ries,⁷ and A. B. Searle.⁸

The author has confined himself in this volume to those varieties of argillaceous rocks most commonly encountered in the course of geological investigations and no attempt is made to widen its province by inclusion of many special and localised types extant. For these the reader is referred to existing text-books devoted entirely to this subject.⁹ Thus restricted, the argillaceous group may be said to comprise the following principal types:—

¹ *Journ. Amer. Ceramic Soc.*, 9, 1926, p. 77.

² *Ohio Geol. Surv.*, 7, p. 52.

³ *Missouri Geol. Surv.*, 11, 1897, p. 25.

⁴ *Geol. Surv. Georgia, Bull.* 6a, 1898, p. 12.

⁵ *Wisconsin Geol. Surv., Bull.* 7, pt. 1, p. 14.

⁶ *W. Virginia Geol. Surv.*, 3, 1906, p. 70.

⁷ "Clays, Occurrence, Properties and Uses." 2nd ed. (Chapman and Hall, London), 1914.

⁸ "Natural History of Clay." (C. Griffen, London), 1912, p. 165.

⁹ H. Ries, *op. cit.*

- (A3. 1) Clay (p. 376).
- (A3. 2) Fireclay (p. 378).
- (A3. 3) Fuller's Earth (p. 380).
- (A3. 4) Æolian Clay (p. 381).
- (A3. 5) Abyssal Clay (p. 382).
- (A3. 6) Volcanic Clay (p. 383).
- (A3. 7) Residual Clay (p. 384).
- (A3. 8) Mudstone (p. 386).
- (A3. 9) Shale (p. 386).

(A3. 1) **CLAY.**

[Pl. 34 A, facing p. 381.]

Def. Clay is essentially a physical state of finely divided mineral matter in which individual diameters of constituent particles range from 0.01 mm. down to colloidal dimensions and in which hydrated aluminous silicates enter chiefly in composition.

Lith. The distinguishing visual feature of true clay is its plasticity when wet, due to adsorbed moisture by the extremely fine mineral particles of which it is composed. Expulsion of that moisture, whether by natural or artificial means, brings about a change of state and the rock passes into a mudstone (A3. 8) or, with the development of lamination, into a shale (A3. 9). Beyond the feel of this rock, recognition of its plastic properties and colour, little is usually discernible from megascopic examination unless organic remains are present, which is a variable feature, depending on stratigraphical horizon. Colour is generally significant. *White* implies absence of iron compounds, carbon or manganese, such clay being essentially composed of hydrated aluminous silicates. *Yellow* suggests incipient oxidation of iron compounds, more rarely chrome ochre. *Brown* clay shows evidence of ferric oxide passing into limonite. *Red* is chiefly due to the presence of ferric oxide (hematite) in finely divided state. *Mauve* colouring suggests manganese dioxide, limonite and sometimes a trace of cobalt compounds. *Purple* is usually due to hydrated manganese dioxide with limonite. *Green* colour may be partly due to finely disseminated chloritic or glauconitic matter, in some cases to the presence of ferrous silicate and ferrous sulphate. *Grey* is inferential of the white type plus admixture of finely divided carbonaceous matter (graphite, carbonised wood, plant fibres etc.). *Black* clay is usually due to an excess of carbonaceous matter, as above, or it may be due to bituminous impregnation; in deoxygenated environments the black colour may be accounted for by amorphous ferrous sulphide, less commonly by black oxide of manganese. The significance of colour as inferential of sedimentary environment is discussed on p. 512. Many examples exhibit blended colouring (variegation).¹ Clays with pebbles, flints, boulders etc., are composite types, the products of particular and local conditions, e.g. glacial boulder clay, clay with flints; in these instances studies of the large components and of the clay-matrix should proceed separately.

Text. Exceedingly fine.

Shape. A to SA.

Min. Comp. Al. Quartz, orthoclase or soda-plagioclase feldspars, primary muscovite, biotite, ilmenite, epidote (in part), tourmaline, zircon, rutile, titanite; less commonly hornblende, garnet. Other accessory minerals are rare.

¹ H. B. Milner, *Proc. Geol. Assoc.*, 36, 1925, p. 313.

Au. Hydrated aluminous silicates, silica, hydroxide and carbonate of iron, muscovite, calcite, chloritic matter, epidote, glauconite, carbonaceous matter, secondary rutile and anatase. Of the hydrated aluminous silicates, the following have been specifically determined;¹ kaolinite, halloysite, beidellite, montmorillonite; others in part determined, in part suspected, include:—allophane, pholerite or nacrite, rectorite, newtonite, cimolite, pyrophyllite, collyrite, schrüterite; in special types the hydrated aluminium oxides gibbsite, diasporé and bauxite occur. Many of the silicate components exist primarily in a colloidal state.

N.B.—Most of these species are separately described in Chapter IX.

Mech. Comp. Grade-size of the detrital particles is <0.01 mm. In many examples the diameters are considerably less; below 0.005 mm. it is extremely difficult to promote deflocculation and secure isolation of particles. Below 0.002 mm. particles are practically in colloidal suspension. Ordinary microscopical observations impracticable on particles of diameters less than about 0.002 mm.

Micro. The difficulty of making a thorough microscopical study of clays from the petrological standpoint has already been emphasised. Where thin sections are available much depends on the skill with which they have been cut, largely a question of the amount of dessiccation and loss of plasticity which has been achieved in preparation of the material. The dried, gently powdered clay forms for the most part the most profitable material to work upon, suitable segregations being made by centrifuging, heavy liquids etc. Much may be learnt about ordinary clays, however, if attention is paid to the following points. Study first the obvious detrital constituents revealed in the prepared concentrates; if these present difficulty on account of extreme fineness proceed by the special technique described for fine material, Chapter III, p. 76, and segregate in the usual way for loose detrital sediments. Quartz is usually in subangular flakes, seldom clear, but turbid with argillaceous matter; check with polarised light. Felspar, if present, is revealed by twin lamellæ in polarised light, *using high power objective*, incidentally essential in all work on clays. Mica is normally of the sericitic type and shows up in the form of silky wisps or flakes of characteristic birefringence and refractive index. Spherulitic siderite may occur in certain varieties. Iron-ores and carbonaceous specks are best displayed by employing strong incident light; this also is of great help in differentiating the aluminous silicates or "clay paste" background in which the detrital particles are set. In thin section polarised light will indicate approximately relative proportions of allogenic to authigenic matter, since quartz is nearly always the most prevalent detrital mineral and is quickly revealed by characteristic interference (usually yellow colours in clay sections owing to the difficulty of producing them to standard thickness); the "clay paste" itself is normally observed to be structureless until high power magnification coupled with reflected light observations are made; then is revealed an organised development of crystalline aggregates, often coloured, sometimes opaque, sprinkled with minute dust particles, probably iron-ores, carbonaceous specks, possibly rutile; such aggregates include one or more of the above-mentioned hydrated aluminous silicate minerals, to be identified in a majority of cases only by exhaustive X-ray, spectroscopic, chemical and optical tests. When kaolinite occurs, it varies in form from tabular, pseudo-hexagonal plates to fan-like sheaves,

¹ See also A. F. Hallimond, *Mem. Geol. Surv., Spec. Rep. Min. Resources Great Britain*, 29, 1925, p. 33; see also *General Refs.*, p. 378.

vermiform or "rouleaux" assemblages of minute crystals;¹ note refractive index and interference colours and compare with quartz; if the stage is rotated, using polarised light, kaolinite in thin section is observed to extinguish more tardily than quartz;² fibrous forms exhibit extinction angles from 15° to 20°; basal cleavage flakes (common occurrence), if not too small, yield biaxial figure. Much of the white, amorphous, powdery or "unglazed porcelain" looking material may be halloysite, quite inert to polarised light; but any particularly abundant, but undeciphered, constituent, should be isolated and fully investigated *per se* to fix its identity.

Types. Fairlight Clay (Wealden), Fairlight, Sussex, variegated clays with spherulitic siderite, lignite and plant remains;^{3, 4} Gault (Upper Cretaceous), grey clay with glauconite, pyrite and *foraminifera*;⁵ Reading Beds (Eocene), West Kent, Surrey etc., mottled clays with plant remains;⁶ London Clay (Eocene), Harefield, Middlesex and elsewhere, bluish-grey clay with pyrite, selenite, calcite etc.;⁷ Upper Oligocene lignitic, white and brown clays of Bovey Tracey, Devonshire;⁸ Pliocene, St. Agnes, Cornwall, brown clay with good detrital constituents;⁹ Glacial Boulder Clay (Cromer Till etc.) of East Anglia, grey unstratified boulder clay with shell-fragments and pebbles of rocks of British and Scandinavian origin etc.^{10, 11}

Refs. ¹ J. A. How, *Handbk. to Coll. Kaolin etc., Mus. Pract. Geol.*, London, 1914, ch. vi, p. 145.

² R. E. Somers, *U.S. Geol. Surv., Bull.* 708, 1922, p. 296.

³ H. B. Milner, *Proc. Geol. Assoc.*, 36, 1925, p. 312; also

⁴ E. Spencer, *Quart. Journ. Geol. Soc.*, 81, 1925, p. 667.

⁵⁻¹⁰ Author's observations.

¹¹ A. J. Jukes-Browne, "Stratigraphical Geology." (Stanford, London), 1912, p. 627.

General Refs.

S. B. Hendricks and W. H. Fry, "The Results of X-Ray and Microscopical Examination of Soil Colloids." *Soil Science*, 29, 1930, p. 457.

P. Urbain, "Introduction a l'étude petrographique et geochemique des roches argilleuses." (Hermann, Paris), 1937.

C. E. Marshall, "The Constitution of the Clay Minerals." *Sci. Prog.*, 30, 1935, p. 422.

C. S. Ross and P. F. Kerr, "The Clay Minerals and their identity." *Journ. Sed. Pet.*, 1, 1931, p. 55; also *U.S. Geol. Surv. Prof. Paper* 165E, 1931.

C. E. Marshall, "Clays as Minerals and Colloids." *Trans. Ceramic Soc.*, 30, 1931, p. 81.

S. I. Tomkief, "Clay Minerals and Bauxitic Minerals etc." *Mineral Mag.*, 23, 1933, p. 463.

Note.—See also bibliography at the end of Chapter XIV.

(A3. 2) FIRECLAY.†

[Pl. 34 B, C, facing p. 381.]

Def. A type of siliceous clay often forming "seat-earth" to coal seams and used for refractory purposes, capable of withstanding high temperature firing without disintegrating or melting.

† Commercial "fireclay" includes a number of differently formed clays and allied rocks suited to various refractory purposes. The term is here restricted to highly siliceous, transported clays of the Coal Measure type, distinct from miscellaneous residual clays, which receive separate consideration in accordance with their undoubted difference in origin and constitution.

Lith. The typical Coal Measure fireclay of the Midlands is a highly siliceous clay, low in alkali and lime content, in some varieties coarse enough for quartz particles to give a "gritty" character to the rock; such approximate petrologically the siltstones (Az. 1) or "grey-wackes" (Az. 6). Generally, however, fireclay is a compact, homogeneous, consolidated clay, with or without lamination. Colour varies from slate-grey to brown or brownish-black, some types possessing a mauve tint. Carbonaceous remains common, sometimes recognisable plant-fragments, more often occurring just as streaks or clots. Coarse varieties have the most detrital material, the finer varieties resembling shale in lithologic character and composition. Types with small silica content are often earthy.

Text. Exceedingly fine; sometimes "soapy"; earthy.

Shape. A to SA.

Min. Comp. Al. Quartz, felspar, muscovite, biotite, occasionally rock-particles, iron-ores and varied accessory minerals. Many examples yield plentiful "heavy" residues.

Au. Mica, chloritic matter and minerals of predominantly micaceous habit (hydrated aluminous silicates), epidote, secondary silica and iron compounds, occasionally calcite and commonly rutile ("clay-slate needles"). These constituents, some or all, form the "clay-paste" especially characteristic of these rocks and for the most part difficult to analyse mineralogically.

Mech. Comp. Average grade 0.01 mm., but detrital quartz often of the silt grade, 0.05 mm. Clay-matter often extremely difficult to break down into individual particles.

Micro. The chief feature of fireclay is the abundance of free quartz in the form of small, equi-dimensional grains of granular habit. In a few varieties these grains are so plentiful as to constitute the rock a siltstone in the strict petrological sense; generally, however, the dark brown matrix is very prominent. Felspar is occasionally diagnosed, but more often is probably represented by decomposition products. The paste includes minute scales of secondary mica, various hydrated aluminous silicates (as for clay, p. 377), iron-ore dust (probably ilmenite) and obvious rutile needles. This form of rutile differs considerably from the primary detrital type; it occurs in slender, acicular crystals, often of perfect formation, almost colourless and with extremely high refractive index; twin forms also observed; J. J. H. Teall records needles of rutile of this type 0.001 mm. in thickness, averaging 0.002 mm., their length being from 8 to 30 times their breadth.¹ Usually where lamination is developed, there is a certain degree of parallelism in the orientation of the detrital elements in the matrix, also discernible in the fibrous minerals of the latter. Where no bedding occurs, the larger grains are distributed haphazardly through the "paste" and the rock is practically devoid of any distinctive micro-structure.

Types. Coal Measure fireclays of Newcastle-on-Tyne etc., Northumberland, coarse and fine laminated varieties;² Middle Coal Measure fireclays of Stockingford, Nuneaton, Warwickshire; Coal Measure clays of Leeds, Halifax and Huddersfield, Yorkshire, typical siliceous clays with carbonaceous matter, micaceous minerals, rutile and other accessories; Millstone Grit, Glenboig Fireclay, Central Valley, Scotland.^{3, 4}

Refs. ¹ *Mineral. Mag.*, 7, 1887, p. 201.

² W. M. Hutchings, *Geol. Mag.*, 1890, p. 264, 316; 1891, p. 164, 304; 1894, p. 34, 64; 1896, p. 309, 346.

³ J. W. Gregory, *Proc. Roy. Soc. Edinburgh*, 30, 1910, p. 348.

⁴ J. S. Flett, *Geology of Glasgow District, Mem. Geol. Surv. Great Britain*, 1911, p. 219.

General Refs.

A. H. Cox, *Geol. Mag.*, 1918, p. 56.

See also *Mem. Geol. Surv. Great Britain Refractory Materials*, 28, 1924, p. 3.

(A3. a) **FULLER'S EARTH.**

[Pl. 34 D, facing p. 381.]

Def. Fuller's Earth is the name given to a particular form of clay composed substantially of what is believed to be montmorillonite, plus anorthoclase feldspar (containing lime), the whole possessing low plasticity and strong decolorising and degreasing properties.

Lith. A soft, earthy rock, of distinctive texture, colour and physical properties. Bedding may or may not be developed. Colour greenish-brown, grey, bluish-grey or yellow. Possesses marked absorbent properties. When scratched with the finger-nail, yields a polished streak. Adheres to the tongue. Crumbles in water and cannot be "mudded."

Text. Very fine, close-grained, powdery or earthy; distinct "clayey" feel.

Shape. SA.

Min. Comp. Al. Quartz, mica, glauconite, calcite; accessory minerals include iron-ores, zircon, apatite, fluorite, locally barite, sphalerite, titanite, galena, hornblende, biotite.¹

Au. Hydrated silicate of aluminium, which makes up the bulk of the rock. "Fuller's earth material," together with anorthoclase feldspar, contains lime.

Mech. Comp. Average grade-size <0.005 mm.

Micro. Difficult to study in thin section. Refractive index, X-ray and chemical methods essential to complete investigation. Usually an abundant and distinctive mineral suite can be separated in the ordinary way. Plant remains and micro-organisms observed. Practically structureless; essentially an aggregate of aluminous silicate particles plus varying amount of detrital constituents.

Types. Fuller's Earth (Bathonian), W. of England;^{2, 3} Fuller's Earth (Lower Cretaceous), Redhill, Nutfield etc., Surrey, with interesting accessory mineral assemblage.^{1, 3}

Refs. ¹ G. M. Davies, *Proc. Croydon Nat. Hist. Soc.*, 1915-16, p. 63, 92, 93.

² A. J. Jukes-Browne, "Stratigraphical Geology." Stanford, London, 1912, p. 415, 422, 424, 425.

³ E. F. Newton, *Proc. Geol. Assoc.*, 48, 1937, p. 175.

General Refs.

J. T. Porter, "Properties and Tests of Fuller's Earth." *U.S. Geol. Surv., Bull.* 315, 1907, p. 268.

C. L. Parsons, "Fuller's Earth." *U.S. Bur. Mines, Bull.* 71, 1913, p. 6.

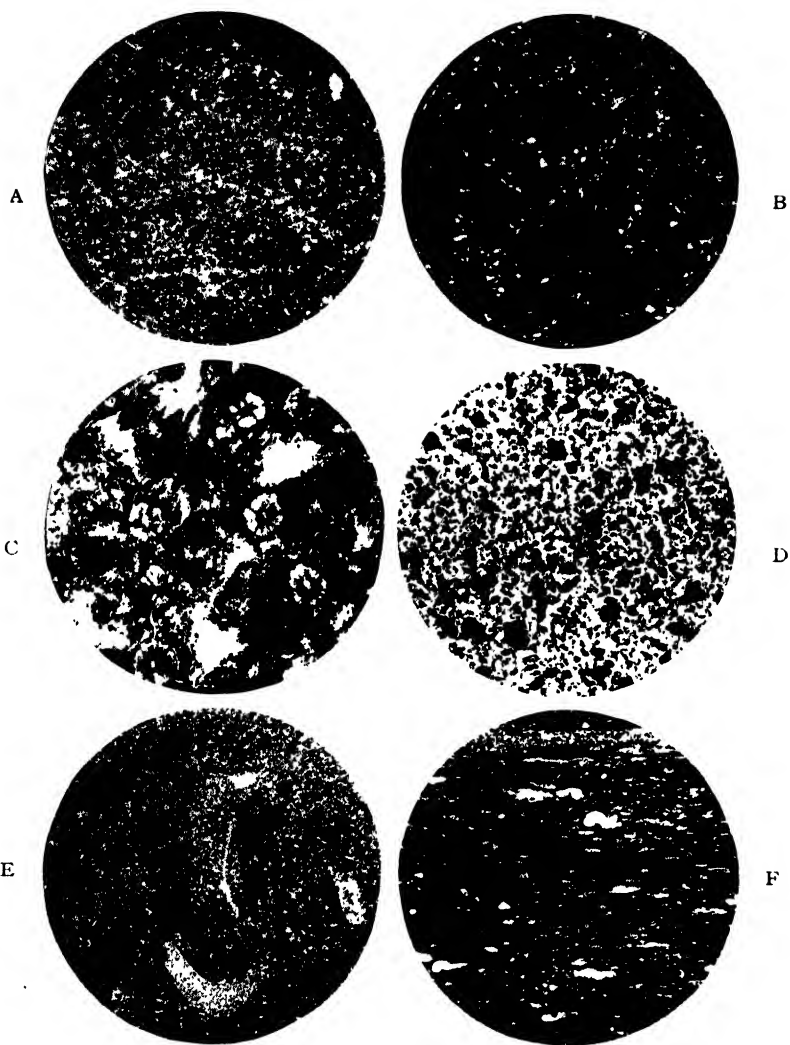
P. G. Nutting, "The Bleaching Earths." *Ind. Eng. Chem., Anal. ed.*, 4, 1932, p. 139.

P. F. Kerr, "Montmorillonite or Smectite as Constituents of Fuller's Earth and Bentonite." *Amer. Min.* 17, 1932, p. 192.

R. E. Grim, "Petrography of Fuller's Earth Deposits etc." *Illinois Geol. Surv., Rep. No.* 26, 1933. Also *Econ. Geol.*, 28, 1933, p. 344.

M. N. Broughton, "Texas Fuller's Earths." *Journ. Sed. Pet.*, 1932, p. 135.

E. F. Newton, *op. cit.*, p. 197.



CLAY, MUDSTONE AND SHALE.

- A. London Clay (Eocene), Ilerne Bay, Kent. [x 20.]
 B. Fireclay (Coal Measures), Stockingford, Nuneaton. [x 25]
 C. Fireclay (Coal Measures), Staffordshire, with spherulitic siderite. [x 13]
 D. Fuller's Earth (Aptian), Surrey. [x 45.]
 E. Mudstone (Up. Lias), West Bay, Dorset. [x 25.]
 F. Monterey Shale (Miocene), Los Angeles, Calif., U.S.A. [x 18.]

(A₃. 4) ÆOLIAN CLAY.

[Fig. 87.]

This subdivision is exemplified by the Eurasian Loess and American Adobe, both partly of æolian and partly of fluvio-glacial origin.

Def. Loess is commonly a yellow, porous silt, clay or marl composed of finely divided mineral matter (? glacial) deposited by wind action. Adobe is a loess-like deposit consisting of fine grained, porous silt and marl deposited in arid desert basins of Western and Central America.

Lith. Yellow, buff, grey or brown calcareous clay, often somewhat silty. Very slightly coherent and easily powdered in the fingers, yet possessing remarkably resistant properties to subærial erosion. Plant remains in various stages of preservation scattered throughout the rock.

Text. Fine, compact, earthy.

Shape. A.

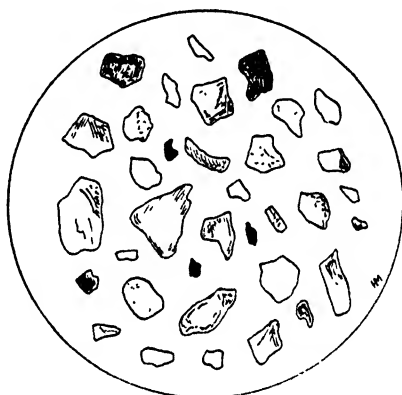


FIG. 87. Grains from the Loess, China. (After G. P. Merrill.)
[x 25.]

Min. Comp. Al. Quartz, orthoclase, plagioclase, muscovite, biotite, magnetite, amphibole, pyroxene etc.

Au. Calcite, dolomite, silica, clay material, carbonaceous matter.

Mech. Comp. Average grade < 0.0025 mm. " Out of 150,000 particles examined under the microscope only about 3% measure above 0.0025 of a millimetre and 1 per cent. over 0.05 of a millimetre " (loess);¹ with adobe the upper limit is about 0.08 mm.

Micro. The constituent particles of this type of deposit are normally very fresh and transparent; their unassorted size and markedly angular shapes are characteristic. When cohesive, the calcareous nature of the cementing medium is seldom in doubt. Vegetable remains prevalent. Practically no organised micro-structure. Microscopical examination confirms the entirely haphazard nature of these deposits.

Types. Loess of China,² Russia, Germany (Rhine Valley) etc.; similar deposits of the Mississippi Valley, U.S.A.;³ adobe of South California, Colorado, Wyoming etc.⁴

Refs. ¹ G. P. Merrill, "Rocks, Rock-Weathering and Soils." (MacMillan, London), 1913, p. 315; also E. V. Emerson, *Journ. Geol.*, 26, 1918, p. 532.

² F. von Richthofen, *China*, vol. i, 1877; also R. Pumpelly, *Amer. Journ. Sci.*, 17, 1879, p. 133.

³ C. R. Keyes, *Amer. Journ. Sci.*, 6, 1898, p. 299.

⁴ I. C. Russell, *Geol. Mag.*, 26, 1889, p. 242, 289.

General Ref.

H. Klähn, "Sedimentation subaerischer Sedimente (Sand und Löss)." *Zeit. Deutsch. Geol. Gesell.*, 85, 1935, p. 35.

(A₃. a) **ABYSSAL CLAY.**

Lith. This subdivision includes varied muds and clays laid down at the greatest depths of the oceans. These rocks are in general very finely divided and are studied as aggregates of incoherent particles from samples dredged from sea-bottom. In certain cases a latent degree of coherency results in solidification to mudstone or shale. Varieties are chiefly distinguished by colour, though there are striking differences in mineral composition revealed by microscopical observations. *Red Mud* owes its colour to ferric oxide. *Red Clay* (so-called) varies from yellowish-red to purple, depending on the ferric oxide and manganese peroxide contents. *Blue* and *Grey Muds* are coloured chiefly by ferrous sulphide plus organic matter, the latter especially characteristic of *Black Muds*; *Green Mud* is largely due to the presence of glauconite.

Text. Extremely fine, soft, often greasy.

Shape. A.

Min. Comp. Al. Quartz, iron-ores, tourmaline, zircon, garnet; where volcanic rocks have contributed, augite, olivine, hypersthene, hornblende, plagioclase, sanidine etc.

Au. Silica, calcite, glauconite, lime phosphate, argillaceous matter.

Mech. Comp. Variable, down to 0.005 mm., but may contain particles of much larger size; some of the "muds" average 0.12 mm.

Micro. Usually a sharp contrast is shown between the organic and inorganic ingredients of these deposits. In the *Red Muds*, quartz and the common terrigenous minerals (above) are associated with diatom frustules, sponge spicules and rarely radiolarian tests. *Red Clay* contains (in order of abundance) magnetite, manganese dioxide, feldspar, glassy volcanic particles, augite, pumice, hornblende, pelagonite, quartz, plagioclase, mica, phillipsite or zeolitic matter, cosmic spherules, sanidine, scoriae, glauconite, olivine, lapilli, rock-fragments, zircon, tourmaline, epidote, garnet. Organic remains include shark teeth, diatoms, *radiolaria*, *foraminifera* etc. *Blue* and *Grey Muds* show quartz, orthoclase, plagioclase, green hornblende, augite, white and black mica, epidote, chloritic matter as flakes, zircon, tourmaline and miscellaneous rock-fragments; glauconite not common. Abundant siliceous and calcareous micro-organisms. The *Black Muds* show variable mineral composition, much quartz, carbonaceous matter, mica etc., with pyrite as a conspicuous constituent; organic remains include planktonic diatoms and pelecypod fragments. *Green Mud* is distinguished by its glauconite, also by some doubtful substance of organic origin. Minerals include quartz, feldspar, magnetite, hornblende, augite, tourmaline, zircon, garnet. In all these deposits, a contribution from submarine volcanic rocks or far-travelled volcanic dust—the product of violent eruption—determines the presence of ordinarily uncommon sedimentary rock minerals.

Types. Deep Sea deposits of the Challenger Expedition, Atlantic, Pacific etc.¹

Refs. ¹ J. Murray and A. F. Renard, "Deep Sea Deposits." Challenger Report, 1891; also L. W. Collet, "Les Depots Marins," 1908.

General Refs.

- H. Scupin, "Ist der Dictyonemashiefer eine Tiefseeablagerung." *Zeit. Deutsch. Geol. Gesell.*, 73, 1921, p. 153.
- R. Ruedemann, "Faunal facies differences of the Utica and Lorraine Shales." *Bull. 267, New York State Mus.*, 1926.
- P. E. Raymond, "The Significance of Red Colour in Sediments." *Amer. Journ. Sci.*, 13, 1927, p. 234.
- R. H. Rastall, "The Petrography of the Hunstanton Red Rock." *Geol. Mag.*, 67, 1930, p. 436.
- H. Williams and O. M. B. Bulman, "The Geology of the Dolwyddelan Syncline (North Wales)." *Quart. Journ. Geol. Soc.*, 87, 1931, p. 425.
- W. H. Twenhofel, "A Treatise on Sedimentation." 2nd ed. (Ballière, Tindall and Cox, London), 1932.
- H. Schmidt, "Die Bionomische Einteilung der Fossilien Meeresboden." *Fort der Geol. und Paläontol.*, 12, 1935.
- F. H. Hatch and R. H. Rastall, "The Petrology of the Sedimentary Rocks." 3rd ed. rev. M. Black (Allen and Unwin, London), 1938.

(A3. *) VOLCANIC CLAY.

Under this heading are placed certain distinctive clays of definite constitution and origin, *e.g.* *bentonite*, implying derivation from devitrified and chemically altered glassy, volcanic ash or tuff. The chief types have been described from America. Closely allied is the abyssal variety of volcanic mud (*q.v.* above).

Lith. Extremely variable in external appearance and superficial properties. Generally well stratified. Colour white, cream, dull green, sometimes blue or pink. Yellow to brown on weathering. Readily absorbs moisture, becoming plastic; excess of water causes formation of slime. Some samples exhibit sandy streaks or patches. Organic remains rare.

Text. Compact, soft; "some have a very loose felt-like texture."¹

Shape. A to SA.

Min. Comp. *Al.* Quartz, felspar, mica, ferromagnesian minerals, zircon, apatite, iron-ores.

Au. Montmorillonite, less commonly beidellite (in bentonite); non-bentonitic clays of similar origin may include halloysite and kaolinite. Abyssal volcanic mud is characterised by siliceous and calcareous matter.

Mech. Comp. Average grade 0.01 mm., but much of the material is of colloidal dimensions.

Micro. In the case of bentonite "microscopic examination between crossed nicols . . . shows that the characteristic mineral of bentonite is crystalline. . . . In some specimens the material is very fine grained, but in most of them the crystal grains can be seen even with low power magnifications. The mineral has a micaceous habit, and moderately high birefringence perpendicular to the cleavage. The groups of plates that have been derived from a single glass fragment commonly have a definite arrangement and sharply outline the original fragment. In most types of bentonite the crystal plates stand perpendicular to the original surface of the glass fragment, and the resulting crystalline area is now composed of two parallel rows of micaceous plates that often have a parting line between them. In

other specimens the micaceous plates have developed parallel to the sides of the glass."¹ Generally the main constituent of these volcanic clays is montmorillonite together with some form of glass, the particles being essentially sections of "bubble boundaries." Detrital quartz tends to be restricted; feldspars and above-mentioned accessory minerals prevalent. These rocks vary in mineral composition, but all present interesting problems in microscopical analysis.

Types. Bentonite, Big Horn Basin, Wyoming, with andesine, orthoclase, biotite and accessory minerals, hydrated aluminous silicates (as above);² also examples from Kansas, Texas, Oklahoma etc.,¹ volcanic mud from deep sea deposits (Challenger Expedition);³ bentonite, Alberta, Canada, associated with coal etc.⁴

Refs. ¹ C. S. Ross and E. V. Shannon, *Journ. Amer. Ceramic Soc.*, 9, 1926, p. 77.

² D. F. Hewett, *Journ. Wash. Acad. Sci.*, 7, 1917, p. 196.

³ J. Murray and A. F. Renard, *Deep Sea Deposits, Challenger Report*, 1891.

⁴ W. H. Twenhofel, "Treatise on Sedimentation." (Ballière, Tindall & Cox, London), 1932.

General Refs.

E. T. Wherry, "Clay derived from volcanic dust in the Pierre of S. Dakota," *Journ. Wash. Acad. Sci.*, 7, 1917, p. 576.

C. S. Ross, "Altered Palæozoic volcanic materials and their recognition." *Bull. Amer. Assoc. Pet. Geol.*, 12, 1928, p. 143.

C. S. Ross, H. D. Miser and L. W. Stephenson, "Water-laid Volcanic Rocks of early and Upper Cretaceous Age in South-Western Arkansas, South-Eastern Oklahoma and North-Eastern Texas." *U.S. Geol. Surv., Prof. Paper*, 154, 1929.

C. S. Ross and P. F. Kerr, "The Clay Minerals and their Identity." *Journ. Sed. Pet.*, 1, 1931, p. 62.

P. F. Kerr, "Bentonite from Ventura, California." *Econ. Geol.*, 26, 1931, p. 153.

(A3. v) **RESIDUAL CLAY.**

Lith. Residual clay, as the name implies, is any clay-material formed *in situ* from the decomposition of some particular rock the minerals of which, by various destabilisation processes, determine the nature of the ultimate clay-substance; in this respect, residual clay differs fundamentally from transported clay. The normal feature of residual clay is the extremely finely divided state of the clay-substance, though often the presence of fragments of miscellaneous rocks and minerals, more resistant to weathering than the parent-substances of the clay, determine an unsorted character. Some degree of plasticity is usually apparent when wet, but with expulsion of moisture, the clay hardens rapidly. Bedding normally absent, but a crude lamination of the solidified material is sometimes apparent. Organic matter not common, but where it occurs is mainly due to plant remains in varied stages of carbonisation. Many residual clays are colourless or only slightly tinged with iron oxide staining; examples are the so-called "*pocket clay*," formed in solution-cavities or pipes in limestone deposits, *bauxite*, *china clay* and *china clay rock*. The more intensely coloured varieties are illustrated by *laterite*, an exceedingly controversial substance which is reddish-brown or yellow.

Text. Exceedingly fine and uniform as far as the clay-substance is concerned; where rock-fragments or "sand" are present, the texture becomes gritty, sometimes even coarse; laterite is variable, some examples being coarse, earthy and friable.

Shape. Clay particles A, less commonly SA. Most embedded rock-fragments are angular, like the components of a breccia. Loose quartz often corroded, therefore rounded.

Min. Comp. Rock-fragments may be of igneous or sedimentary origin; in "pocket clay" they are less common, but include limestone, dolomitic limestone, occasionally basic igneous rocks; bauxite is, on the whole, remarkably free from large constituents, though fragments of basalt have been noted in one case; china clay and china stone (china clay rock) often include quartz-tourmaline rock (schorl), pegmatite, altered granite, cassiterite; laterite may comprise fragments of mother-rock, e.g. lava, basalt, granite, gneiss, also sandstone. The finer mineral components are quartz, hematite, limonite and varied accessory minerals; in china clay a distinctive assemblage of quartz, tourmaline, topaz, mica, cassiterite, fluorite, is characteristic. The clay-substance varies considerably; in pocket clay it is predominantly hydrated aluminous silicate, with kaolinite, halloysite, possibly montmorillonite etc.; in bauxite it is essentially alumina and some form of ferric hydrate (? goethite or limonite), as is the case with laterite; the alumina may be represented either by gibbsite (p. 287) or diaspor (p. 275), though often the clay-substance gives the impression of being an amorphous mixture rather than individualised species.

Mech. Comp. Clay-material extremely fine, often colloidal. Gritty constituents usually conform to the medium sand-grade.

Micro. The "floating" minerals or rock-fragments are the first components to attract attention and seldom present great difficulty in diagnosis. It is usual to find quite an arbitrary distribution of these constituents in the clay-mass, no particular relationship between the two being apparent. The clay-substance may or may not present a certain degree of micro-structure; in pocket clay it is reduced to a minimum unless much crystalline kaolinite is present, when the interlocking scaly plates of that mineral are discernible. Bauxite is frequently quite without structure, though in some examples a fibrous character (? gibbsite) with enveloping brown material (ferric oxide or hydrate) is conspicuous. In china clay, colourless, pseudo-hexagonal, scaly plates of kaolinite are associated with corroded quartz, white mica, topaz etc., often in the form of interlocking crystal-masses set promiscuously in a very fine kaolinitic cement; the latter may include material having the properties of halloysite. Laterite presents considerable variation in micro-structure. Scales and fibres due to gibbsite may be observed, these often picked out by ferric hydrate staining; intimately mixed with this material are quartz particles, iron-ores, carbonaceous matter etc. Diaspor has been recorded from some varieties of laterite, which in many respects closely resembles bauxite in micro-structure.

Types. "Pocket clay" from the Carboniferous Limestone of Derbyshire, Staffordshire etc.;¹ bauxite deposits of Antrim;² china clay of West Cornwall;^{3, 4, 5} laterite of India,⁶ Seychelle Islands,⁷ French Guinea⁸ etc.

Refs. ¹ Author's observations.

² "The Intra-basaltic Rocks of N.E. Ireland." *Mem. Geol. Surv., Ireland*, 1912.

³ A. Howe, "Handbook to the Collection of Kaolin." *Mus. Pract. Geol.* 1914, p. 145.

⁴ *Mem. Geol. Surv.*, 347, 1909, ch. ix.

⁵ J. W. Gregory, "Elements of Economic Geology." (Methuen, London), 1928, ch. xiii.

* T. H. Holland, *Geol. Mag.*, 1903, p. 59, and refs. cited.

† M. Bauer, "Beitrage zur Geol. der Setchellen." *Neues Jahr. für Min.* etc. 1898, 2, p. 163.

‡ L. L. Fermor, *Geol. Mag.*, 1915, p. 28, 77, 123.

General Refs.

T. V. M. Rao, "A Study of Bauxite." *Mineral. Mag.*, 21, 1928, p. 407.

C. S. Fox, "Bauxite and Aluminous Laterite." (Crosby, Lockwood, London), 1932; also *Geol. Mag.*, 69, 1932, p. 559.

(A3. a) MUDSTONE.

[Pl. 34 E, facing p. 381.]

Def. An indurated non-laminated sediment composed of finely divided mineral matter of clay grade and composition.

Lith. Consolidation of clay without the production of fissile characters results in a type of rock to which, for want of a better name, the term "mudstone" is applied; "claystone" would suit equally well. The coarser varieties have affinities with "siltstones" (p. 373). Chief lithological characters are colour, as variable as in clays, though usually dark green, brown or grey or a blend of these and an absence of anything but the crudest lamination. Organic remains, especially carbonaceous, very common. Oblique jointing and limonitic staining on planes thus developed are frequent features.

Text. Very fine; smooth surfaces.

Shape. A to SA.

Min. Comp. As for clay (*q.v.* p. 376).

Mech. Comp. Average particle dimensions <0.01 mm. Much of the material is in a very fine state of division and is ultra-microscopic. (See relevant remarks under Clay, p. 377.)

Micro. Although this rock-type lacks lamination, some degree of parallelism of orientation of constituent minerals is often discernible under the microscope, the result of compaction. Detrital matter together with organic remains if present is set in a fine clay-matrix in which certain components, *e.g.* silica, calcite, limonite, carbonaceous matter and one or more hydrated aluminous silicates, can be recognised. Predominant calcite or dolomite gives distinctive "calcite" or "dolomite mudstones." With development of chamosite, siderite etc., these rocks pass naturally into sedimentary ironstones (*q.v.* p. 423). Mudstones are sometimes traversed by veins of secondary silica or calcite carrying pyrite and related iron or copper ores. In certain types white mica, chloritic matter and secondary rutile are produced as a result of induration, such constituents forming a felted mass wrapping round quartz and the larger components.

Types. Graptolitic mudstones, Ordovician and Silurian, Welsh Borders;¹ Liassic mudstones (calcareous, pyrite and carbonaceous matter), Bridport, Dorset;² Wealden, Weald Clay mudstones, Sussex, Kent etc.³

Refs. 1, 2, 3 Author's observations.

General Refs.

J. J. H. Teall, *Mineral. Mag.*, 7, 1887, p. 201-204 (for rutile needles etc.).

G. W. Tyrrell, "Principles of Petrology." (Methuen, London), 1926, p. 214.

(A3. a) SHALE.

[Pl. 34 F, facing p. 381.]

Def. An indurated, laminated sediment composed of finely divided mineral matter of clay grade and composition.

Lith. Shale differs fundamentally from mudstone in its possession of definite laminations or bedding planes, parallel to which it splits with comparative ease. It represents, in fact, one stage further in consolidation of clay, mud etc., than mudstone. Lamination may be thin or thick and is accordingly significant. Many fluviatile or lacustrine shales exhibit remarkably thin laminæ, for instance, varve shales. Colour, as with clays (q.v. p. 376), frequently suggests conditions of deposition; grey, black or blue shales are usually derived from muds of marine, estuarine or fluviatile origin initially rich in carbonaceous and sulphide materials; these are the commonest types. Red shale owes its colour mainly to ferric oxide; green shale chiefly to chloritic material resulting from ferromagnesian mineral decomposition. Organic remains, both animal and vegetable, very prevalent; there is often an inherent relationship between nature and quantity of organisms and the colour of the shale: see ref. 1, p. 388. Lignite seams and secondary pyrite common, especially in estuarine and fresh-water types; mineralised veins, e.g. calcite, quartz, barite, often developed; prominent jointing observed at right angles or obliquely to the laminæ, or both.

Text. Fine, smooth; with inclusion of sand becomes gritty.

Shape. A to SA.

Min. Comp. Al. Quartz, mica, iron-ores and varied accessory minerals; occasionally feldspar.

Au. Secondary silica, calcite, limonite; usually abundant chloritic matter, amorphous carbon, rutile needles; less commonly titanite, leucoxene. Much of the "background" of these rocks is indecipherable and represents products of induration of aluminous silicates such as are found in clays.

Mech. Comp. Detrital particles vary from silt to clay grade, usually, however, conforming to the former limits, 0.1-0.01 mm.; the finer particles are of true clay dimensions, frequently unmeasurable by ordinary means.

Micro. The dominant character of shale is the parallel orientation of its constituents, both organic and inorganic, revealed by thin section; such parallelism is best observed in sections cut transverse to the bedding, but the study should always be supplemented by sections cut parallel to the bedding. The latter show the mutual relationship of the constituents as they lie along one bedding-plane of the rock; in the case of organisms, e.g. plant spores, this amounts to a horizontal section; the relative proportion of detritus to shale-substance is also conspicuous in such horizontal sections. Transverse sections reveal the nature of the bedding, slight changes in constitution of material with alternating laminæ and longitudinal or cross-sections both of minerals and organisms. Products of infiltrating solutions deposited along bedding-planes, in veins or cracks at right angles or obliquely to these, are also readily studied by such transverse sections. Usually the contrast between parallel and transverse sections is very marked. Shale-substance may be difficult to decipher, but the titanium minerals are normally conspicuous; much of the brown, translucent matter in many varieties is of carbonaceous origin and is frequently optically inert. Investigation by reflected light is often helpful, when limonite, aluminous silicate, secondary silica, green chloritic material etc., may be clearly picked out in the mass. Muscovite, the ubiquitous shale mineral, presents characteristic features and is seldom difficult to diagnose. Accessory minerals must be studied from pulverised rock.

sence of magnesia, indicating magnesium carbonate. Anhydrite, gypsum, barite, celestite, are locally prevalent. Glauconite common in marine types.

Micro. Under the microscope marls present much the same features as clays; the detrital constituents are scattered haphazardly through a matrix in which much of the material is difficult, if not impossible, of diagnosis in terms of known minerals. Calcareous matter is generally betrayed by "twinkling" on rotating the polariser alone. Sulphates, if present, are often finely crystallised in fibrous aggregates of patchy occurrence. In coloured varieties the pigment is observed either as a staining material for the bulk of the rock or as irregular streaks traversing it. Where glauconite is in evidence, it frequently exhibits organic structure, *e.g.* *foraminifera*, and gives a distinctive appearance and colour to the rock. For the rest, the main mass of the rock is structureless unless the component minerals of the matrix can be made out, when a mosaic of equi-dimensional particles, often interrupted by dense interstitial matter, may be observed.

Types. Keuper Marls of Leicestershire. different coloured marls with gypsum etc.;¹ also of the Bristol district with variegated green, red and purple tints;² Chalk Marl of England, with glauconite etc., and "Chloritic Marl," Dorset, Isle of Wight etc.;³ Oligocene (Bembridge) marls, Isle of Wight, white, red and blue marls with calcareous concretions and freshwater shells.⁴

Refs. ¹ T. O. Bosworth, "Keuper Marls around Charnwood, Leicester." *Leicester Lit. and Phil. Soc.*, 1912.

² Author's observations.

³ W. Hill, "Cretaceous Rocks of Britain." *Mem. Geol. Surv.*, 2, 1903, ch. xxii.

⁴ J. W. Judd, *Quart. Journ. Geol. Soc.*, 36, 1880, p. 169, and E. Keeping, *Geol. Mag.*, 1887, p. 48.

General Refs.

C. A. Davis, "A Contribution to the Natural History of Marl." *Journ. Geol.*, 8, 1900, p. 485; also "A Second Contribution to the Natural History of Marl." *Journ. Geol.*, 9, 1901, p. 491; also "Natural History of Marl." *Geol. Surv. Michigan*, 8, 1903.

(AB. 3) CALCAREOUS SHALE.

Def. An indurated, laminated sediment composed of finely divided mineral matter of clay grade and composition which also includes a substantial proportion of calcareous material. An indurated marl.

Lith. Shale in which occurs an appreciable quantity of lime is designated as calcareous shale, though no particular quantity has ever been specified; the term consequently has a wide and varied interpretation. It should be confined to indurated marl in which definite laminæ have been produced as a result of compaction, a stage further in consolidation of marlstone. Argillaceous matter, however, is always in excess of calcareous in these rocks. Superficially there may be little to differentiate calcareous from ordinary shale, though the former is usually rather paler in colour than the latter, commonly grey, yellow, brownish-white. Lamination is often extremely fine; where the calcareous matter is concentrated in some layers more than others, alternating light and dark colour-banding may be manifest. Organic remains common.

Text. Very fine.

Shape. SA.

Min. Comp. Al. As for Shale (*q.v.* p. 387).

Au. Calcareous matter in addition to the normal shale minerals (p. 387), but often with much less rutile and limonite; silica is usually abundant and amorphous carbonaceous matter prevalent in dark coloured types.

Mech. Comp. The bulk of the material composing these rocks is very fine indeed, <0.005 mm., the tendency to extremely fine particle dimensions increasing with amount of lime.

Micro. The presence of calcite in these rocks is revealed by the ordinary "twinkling" with the polariser alone. In some instances, however, chemical analysis may show the presence of lime in excess of that necessary to satisfy specific minerals and which might be anticipated in the form of a calcareous cement, yet no optical reaction can be discerned. As the rock passes more into the true limestone, calcite *per se* becomes prominent; argillaceous matter diminishes and the hybrid type "argillaceous limestone" (*q.v.* p. 394) is produced; this tends to exhibit certain characteristic microscopic features differentiating it from the type here under consideration. The study of calcareous shales should proceed as with ordinary shales, two sections being desirable, one parallel and one transverse to the laminae. If reaction for calcite is positive, note particularly the strength and nature of development of this material, what relationship it bears to included organisms (if any), to detrital quartz and to associated authigenic matter.

Types. Silurian (Woolhope) calcareous shale, Shropshire (Coalbrookdale, etc.);¹ Devonian Calceola Shales, South Devonshire;² Lias, Bridport, Dorset, calcareous shale in which the cementing matter can be well studied;³ Oxfordian, Weymouth, Dorset, with free calcite, pyrite, plant remains and fine laminations;⁴ Lower and Middle Purbeck, Dorset, calcareous shales with abundant organic remains, very fine laminae, plant remains;⁵ Wadhurst Clay (Wealden) shales, with lignite, pyrite, fine laminae and colour-banding.⁶

Refs. ¹ A. J. Jukes-Browne, "Stratigraphical Geology." (Stanford, London), 1912, p. 165.

² W. A. E. Ussher, *Quart. Journ. Geol. Soc.*, 46, 1890, p. 499.

^{3, 4, 5, 6} Author's observations.

(B) Organic Origin

In this category are placed all those sediments owing their origin essentially to accumulation of organic matter of diversified nature. In contrast to rocks of mechanical origin which, as now explained, imply transport of constituents in a majority of cases, rocks of organic origin are for the most part formed *in situ*; they represent accumulations of the harder parts or more stable components of both animal and vegetable matter in environments and under conditions differing considerably from those normal to detrital sediments. These fundamental differences of origin are amply reflected by the rocks themselves, both in composition and micro-structure. The purest types are composed entirely of organic matter, but these are compara-

tively scarce in nature; usually a small but appreciable amount of mechanically-born sediment is apparent to emphasise the influence, even at a distance, of terrigenous material; with increase in proportion of detrital constituents, less pure types are evolved and gradually the gap is bridged between the two primary divisions of sedimentary rocks, *i.e.* of mechanical and organic origins (Groups A and B). Further, these organically-formed rocks are inherently susceptible to alteration both during and subsequent to consolidation by chemical reactions set up as a result of access of various substances in solution (metasomatism). Such changes are, when widespread and comprehensive, productive of types closely related to sediments fundamentally of inorganic chemical origin (Group C).

Intensive petrographic study of these rocks implies a working knowledge of the essentials of palæontology and, to a lesser extent, of palæobotany, since three main features come under observation in all cases: the organic remains, the matrix or cement (which may be of biochemical or simply of inorganic origin) and the inherent structure, *i.e.* relationship of organic constituents to matrix. To this must be added, in appropriate instances, the determination of foreign, mostly detrital, occasionally submarine volcanic or other igneous matter. Where marked changes in chemical composition are involved, a knowledge of theoretical interactions between the fundamental minerals, salts in solution or reactive substances in aqueous suspension helps considerably in the interpretation of the phenomena displayed.

For present purposes, rocks in this category may be subdivided into five groups on the basis of characteristic biochemical composition:—

(B1) CALCAREOUS (p. 391).

(B2) SILICEOUS (p. 400).

(B3) FERRUGINOUS (p. 405).

(B4) CARBONACEOUS (p. 406).

(B5) PHOSPHATIC (p. 417).

(B1). CALCAREOUS DEPOSITS. These comprise limestones built up by the accumulation of varied fossil (or recent) shell-fragments, corals, micro-organisms etc., set in a matrix mainly of organic, to a lesser extent of inorganic origin. Dis-

tinctive types are determined by characteristic fossils, by peculiar structures or by the presence of particular compounds or impurities. Some degree of consolidation is common to all except the abyssal oozes conveniently considered here. Thus we may recognise:—

(B1. 1) Limestone (including distinctive fossil types (p. 392).

(B1. 2) Dolomitic Limestone (p. 395).

(B1. 3) Oolitic and Pisolitic Limestone (p. 397).

(B1. 4) Abyssal Ooze (p. 398).

(B1. 5) Chalk (p. 399).

(B1. 1) **LIMESTONE.**

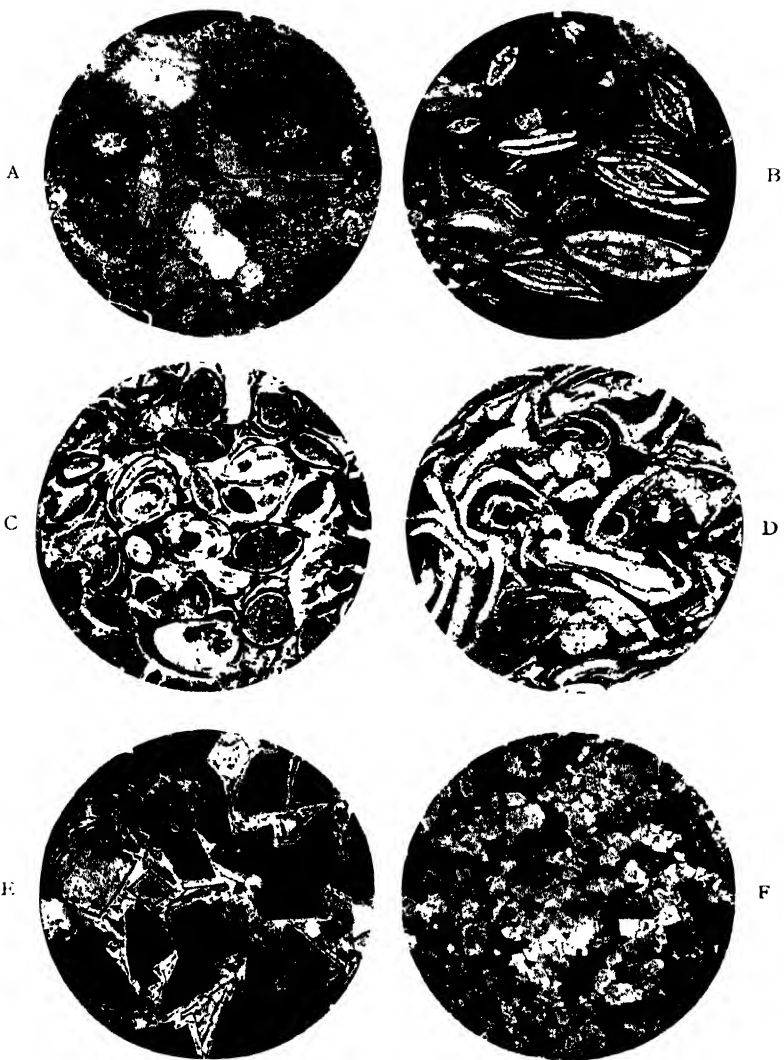
[Pl. 35 D and E, facing p. 388, and Pl. 36 A-D, facing p. 392.]

Def. Limestone is the name applied to stratified rocks chiefly of organic origin and consisting substantially of calcium carbonate.

Lith. Extremely variable, depending primarily on the nature and quantity of fossil fragments present, on their degree of preservation and cementation; also on the purity of the rock as determined by foreign matter or secondary constituents developed. Every gradation from fine, compact, close-grained type, void of recognisable organisms, to coarse shelly limestone occurs. Where organic remains are scanty or wanting and cement predominates, coarse to fine crystalline characters may be observed. In some examples composed of mutually interferent calcite crystals of megascopic size and uniformity of dimensions, the "sugary" or "saccharoidal" character is apparent. Contrasted are those types in which the rock is made up of a homogeneous aggregate of microcrystalline calcite particles etc., with difficulty distinguishable lithologically from certain compact grits or quartzites. In doubtful cases the acid test should always be applied: with normal limestone effervescence when cold is marked.

Colour is a rough guide to purity; white, cream-coloured, yellow and pale grey rocks are normally the most free from detrital and other contamination; red limestone implies disseminated oxide of iron; brown to chocolate-brown developments are mainly produced by strong impregnation of limonite; dark grey to black types depend largely on finely disseminated carbonaceous matter; greyish-brown or ochreous rocks often imply the presence of considerable argillaceous matter. Appreciable amounts of detrital quartz result in gritty or sandy limestone; when excessive, the rock passes into calcareous sandstone or grit (p. 368). Bedding normally developed, but may not be apparent in hand-specimen; more commonly observed in the finer, non-shelly types. Limestones are frequently the host of metalliferous and other minerals which may in certain cases be conspicuous; mineral veins, e.g. silica, calcite, fluorite etc., are often observed traversing the rock in all directions. Prominent structures determined by oolitic or pisolitic developments are separately noticed (B1. 3, p. 397).

The following are among the common organic contributors to these rocks, whose remains are often determinable megascopically:—*brachiopoda*, *actinozoa* (corals), *crustacea* (in particular the *ostracoda*), *echinoderma* (including the *crinoidea*), *foraminifera* (in part), *mollusca*



LIMESTONE AND DOLOMITIC LIMESTONE.

- A. Crinoidal Limestone (Carboniferous), Skrinkle Bay, Pembroke. [x 15.]
 B. Nummulitic Limestone (Eocene), Cairo, Egypt. [x 15.]
 C. Ostracod Limestone (Purbeckian), Swanage, Dorset. [x 15.]
 D. Shelly Limestone, "Purbeck Marble" (Purbeckian), Purbeck, Dorset.
 [x 15.]
 E. Dolomitic Limestone (Permian), Mansfield Woodhouse, Notts. [x 15.]
 F. Dolomitic Limestone (Palaeozoic), Malew, I.O.M. [x 23.]

(lamellibranchs and gasteropods). *Algæ*, *foraminifera*, *polyzoa* or *bryozoa* and more rarely *pteropoda*, are among the well-known micro-organic contributors to these rocks.

Text. Highly variable, entirely dependent on presence (or absence) and size of organic remains, also on degree of compaction of the cementing material. The average type is probably of medium texture; many unfossiliferous limestones are very close-grained, particles averaging 0.1-0.2 mm., and are thus fine-textured rocks.

Shape. Organic fragments tend to preserve something of their essential morphology, though brittle shells may be disintegrated into several highly angular parts by compaction of the rock. Crystalline cementing material exerts its inherent tendency to produce natural shape, though this may be prevented where there is excess of material. Detrital particles usually exhibit considerable rounding.

Min. Comp. *Al.* When detrital matter occurs, it usually consists of quartz, iron-ores (chiefly ilmenite), tourmaline, zircon and garnet, *i.e.* the stable accessory minerals. In a few instances the detrital suite may be considerably enriched, *e.g.* contribution of material from submarine volcanic rocks etc. Shallow-water limestones appear to contain most allogenic minerals. F. Smithson observes that limestones associated with sandstones tend to be richer in detrital minerals than the latter rocks, due possibly to preservation of the less stable minerals by protective calcite envelopments.¹

Au. Calcareous mud, either in the form of finely divided amorphous material or as crystalline calcite: the latter may represent a product of recrystallisation. Silica is sometimes chalcedonic, often cryptocrystalline, or may occur as secondary quartz frequently doubly terminated. Limonite, hematite, carbonaceous matter and/or argillaceous material common; locally fluorite (Derbyshire). With advent of magnesium carbonate, the rock passes into a dolomitic limestone, type B1. 2 (q.v. p. 395).

Organic Material. This may imply the presence of calcite, aragonite, less commonly of silica. Calcareous *algæ* are composed either of calcite or aragonite; similarly the corals (*actinozoa*) and *polyzoa*. *Crustacean* tests are mainly calcite, chitinous material, less commonly phosphate of lime; *brachiopoda* and *echinoderma* are of calcite, similarly the vitreous forms of *foraminifera*; the porcellaneous forms of the latter are probably of aragonite in most cases. *Lamellibranchia* vary, certain genera (*e.g.* *Trigonia*, *Pinna*, *Spondylus*, *Unio* etc.) exhibiting an inner shell-layer of aragonite, the outer being of calcite; *Ostrea*, *Pecten* etc., are entirely of calcite, otherwise many forms are composed of aragonite. *Gasteropoda* are mainly of aragonite; a few combine both minerals (*e.g.* *Littorina*). *Fusinus* is entirely of calcite. *Pteropoda* are chiefly aragonite. *Porifera* (sponges) are composed both of calcite (calcareous sponges) and silica. Most *cephalopod* remains are composed of aragonite, but the guard of *helemites* is of calcite. Replacement of such original organic substance by silica, limonite, marcasite or pyrite, rarely by calcium sulphate, barite etc., is possible.

Mech. Comp. Concerns only detrital ingredients which are usually very fine, 0.1-0.01 mm.

Micro. Investigations of limestones in this section should proceed methodically. Where organic remains are present, study these first. The arrangement of the mineral substance forming the shells or hard parts may be concentric, radial, tangential or combinations of these. Radial arrangement results in the "black cross" effect in doubly

¹ Written communication.

polarised light. Sometimes the shell-fragments are thick, cloudy or opaque. Micro-organisms, *e.g.* *foramanifera*, *algæ*, *radiolaria*, *diatoms* etc., are always significant and often well preserved, either as original carbonate or silica, or replaced by pyrite, glauconite etc. Calcite and aragonite as fossil-shell substance are often impossible to differentiate positively under the microscope: see p. 258. Next investigate the matrix of the rock. If megascopic or larger microscopic organisms are plentiful, this may be reduced to enveloping or interstitial material; with impoverishment of visible organisms, the matrix dominates and characterises the rock. Usually it presents a mosaic of mutually interfering calcite crystals representing coarsely or finely recrystallised calcareous mud; sometimes the muddy character prevails, when much of the cement appears optically inert; nevertheless it shows up well by reflected light. Veins of secondary silica, deep bluish-grey birefringence tint, or of interlocking quartz crystals, may also traverse the rock, or may be distributed haphazardly in the calcite cement. Colouring matter denotes impurity, usually due to iron compounds. Detrital matter should be searched for under high power objective in the cementing medium (alternatively isolated by crushing the rock (p. 80)); this examination may also reveal minute organisms scattered through the mass. Every transition from the normal limestone to dolomitic, oolitic and other types must be anticipated and will be easily decipherable under the microscope. The structure of limestones is primarily determined by the relationship of organic fragments or of prolific micro-organisms to the matrix or, where organisms are lacking, by arrangement of the components of the matrix, presence or absence of definite orientation, or by special developments (*e.g.* oolites, p. 397). Careful scrutiny of the closeness or sparseness of spacing of the fossil elements in the cement is significant, often diagnostic for a particular horizon in the limestone formation. Similarly the manner of distribution of micro-organisms in a finely divided matrix should be noted. Secondary structures determined by mineral veins, argillaceous matter in bands, patches of siliceous material, chert development etc., should all be carefully investigated and recorded.

The results of microscopical examination, by determination of specific organisms characteristic of the rock, lead to its correct definition. Thus the following varieties may be separated, each distinguished by the presence to a greater or lesser extent of the forms identified:—

- a. *Algal limestone*, *e.g.* *Lithothamnion* and *Chara* limestones.
- b. *Bryozoan limestone*, *e.g.* *Fenestella* limestone.
- c. *Coral limestone*, *e.g.* *Alveolite* limestone.
- d. *Crinoidal limestone*, *e.g.* *Encrinure* (*Encrinurus*) limestone.
- e. *Crustacean limestone*, *e.g.* *Ostracod* limestone.
- f. *Echinoid limestone*, *e.g.* *Nucleolite* (*Echinobrissus*) limestone.
- g. *Foraminiferal limestone*, *e.g.* *Nummulitic* limestone.
- h. *Shelly limestone*, made up largely of miscellaneous fossil-shell fragments, chiefly *mollusca* and *brachiopoda*.

With increase of impurity in the form of argillaceous matter, the so-called "argillaceous limestone" or "cement-stone" is produced. This variety embodies the normal features of limestone, but the matrix contains a good deal of finely divided clay-substance, much of it optically inert; sometimes the clay-substance is distributed regularly throughout the rock, in other cases it occurs in patches, often enclosing visible detrital quartz.

Types. Cambrian, Durness Limestone, N.W. Highlands of Scotland, Skye etc., with sponge remains, sometimes partially dolomitised, some examples "saccharoidal";¹ Ordovician, Bala Limestone, Bala, North Wales, with calcareous and siliceous mud, crinoids, polyzoa etc.;² also the Corona Beds (of same age), Cross Fell, Westmorland, crustacean limestone (*Beyrichia*);³ Silurian, Wenlock Limestone, Shropshire, often impure rock with abundant corals, also crinoids and polyzoa;⁴ Aymestry Limestone, Silurian, Shropshire, earthy limestone with brachiopods ("Pentamerus (*Conchidium*) Limestone");⁵ Devonian limestone, Devonshire, corals and crinoids;⁶ Old Red Sandstone "Cornstone," Welsh Borders, nodular, argillaceous limestone, much amorphous matter;⁷ Carboniferous Limestone, Bristol district, Forest of Dean, etc., crinoidal and shelly limestone;⁸ Lias, Barrow-on-Soar, Leicestershire, argillaceous limestone ("Cement Stone") with shell-fragments, fish scales etc.;⁹ Portlandian, massive limestone, often with much calcareous mud, shell-fragments, secondary silica etc.;¹⁰ Purbeckian (Upper Purbeck) "Marble," Dorset, Wiltshire etc.; freshwater limestone with gasteropod (*Paludina*) and lamellibranch fragments (Cyrena, Unio etc.), also plant remains;¹¹ Eocene, Cairo, Egypt, foraminiferal limestone ("Nummulitic Limestone");¹² Oligocene, Bembridge Limestone, marly or concretionary, freshwater limestone with *algæ* (*Chara*), gasteropods and curious oviform bodies, said to be "the eggs of the large *Amphidromus*."¹³

Refs. ¹ "Geology N.W. Highlands." *Mem. Geol. Surv. Scot.*, 1907, p. 375.

² A. J. Jukes-Browne, "Stratigraphical Geology." (Stanford, London), 1912, p. 125.

³ J. E. Marr, *Geol. Mag.*, 1892, p. 97.

⁴ A. J. Jukes-Browne, *op. cit.*, p. 165; A. Harker, "Petrology for Students." (University Press, Cambridge), 1919, p. 236.

⁵ A. J. Jukes-Browne, *op. cit.*, p. 167.

⁶ E. Wethered, *Quart. Journ. Geol. Soc.*, 48, 1892, p. 377.

⁷ A. Heard and R. Davies, *Quart. Journ. Geol. Soc.*, 80, 1924, p. 504.

⁸ E. Wethered, *Geol. Mag.*, 1886, p. 529.

⁹ Author's observations.

¹⁰ F. H. Edmunds and R. J. Schaffer, "Portland Stone etc." *Proc. Geol. Assoc.*, 43, 1932, p. 225.

¹¹ W. R. Andrews and A. J. Jukes-Browne, *Quart. Journ. Geol. Soc.*, 50, 1894, p. 59 (Vale of Wardour); A. Strahan, "Geology of Isle of Purbeck." *Mem. Geol. Surv.*, 1898, p. 79, 80; H. B. Woodward, "Jurassic Rocks of Britain." *Mem. Geol. Surv.*, 5, 1894

¹² Author's observations.

¹³ J. W. Judd, *Quart. Journ. Geol. Soc.*, 36, 1880, p. 169; also E. Keeping, *Geol. Mag.*, 1887, p. 48; A. J. Jukes-Browne, *op. cit.*, p. 561.

General Refs.

H. C. Sorby, *Quart. Journ. Geol. Soc.*, 35, 1879, p. 56.

J. G. Goodchild, *Geol. Mag.*, 1890, p. 71.

E. W. Skeats, *Bull. Mus. Comp. Zool. Harvard*, 42, 1903, p. 53.

L. Cayeux, "Les Roches Sédimentaires de France: Roches Carbonates." (Masson et Cie, Paris), 1935.

(B1. 2) DOLOMITIC LIMESTONE.

[Pl. 36 E and F, facing p. 392, and Pl. 37 A, facing p. 397.]

Def. A limestone containing a substantial proportion of dolomite.

Lith. The true dolomitic limestone is one containing the mineral dolomite, but in which calcium carbonate predominates. In outward

appearance there is often nothing specific to suggest the presence of dolomite and even under the microscope, if the familiar dolomite "rhombs" are not developed, diagnosis may not be positive in the absence of chemical test (p. 258). On the other hand, many dolomitic limestones are sufficiently distinctive in microscopical characters to warrant the separation of the type from ordinary limestones. Megascopic characters of dolomitic limestones include compactness, closeness of grain, cellular structure, usually a white, cream or grey colour; their appearance *en masse* is often nodular, concretionary, thick bedded, conspicuously jointed, sometimes massive. Organic remains are common, but may be obliterated by dolomitisation; they often show a tendency to weather out on the surface of the rock, e.g. sponge limestone (Durness dolomitic limestone, Skye, N.B.).¹ Bedding may or may not be apparent in the hand-specimen.

Text. Usually medium to fine; sometimes earthy.

Shape. Concerns detrital particles only: usually rounded. In so far as dolomite is concerned, this mineral often builds very perfect rhombs, producing a highly angular mosaic.

Min. Comp. Al. As for limestone (Bt. 1, p. 393).

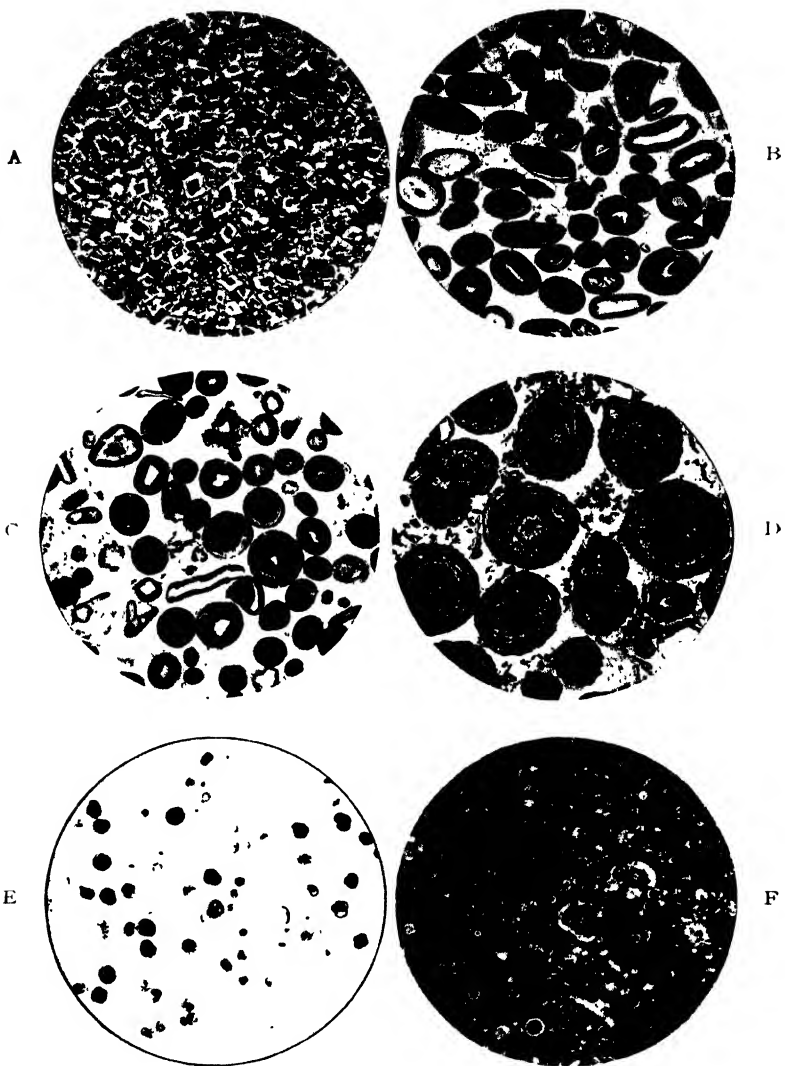
Au. Calcite, dolomite, silica, hematite, limonite, less commonly argillaceous matter and carbon; also sulphates.

Organic material. As for limestone, but *foraminifera*, corals and *polyzoa* tend to predominate.

Mech. Comp. Detrital constituents usually very fine: <0.05 mm.

Micro. Under the microscope every stage from incipient to partial or complete dolomitisation can be traced. Incomplete dolomitisation usually implies the change subsequent to deposition of the original limestone; complete dolomitisation may denote contemporaneous process with deposition. In the case of complete achievement, much of the original organic remains may be obliterated and specific identification be thereby rendered impossible; in such examples the dolomite assumes a crystalline or granular form. Where partial change is manifest, the dolomite is detected for the greater part in the matrix; if crystalline (in rhombs) it will at once be apparent; if granular or disseminated as fine dolomitic mud, it may be amorphous or almost cryptocrystalline, when staining will be necessary for its differentiation from calcite. In some examples dolomite rhombs or other crystal forms show the presence of impurities such as hematite, arranged in geometrical fashion sympathetically with the outlines of the crystal. Secondary silica is often noted in the interstices of the crystals. Alternatively, where the limestone was originally impure with admixture of argillaceous matter, this is seen to form a dirty, usually impenetrable background to the dolomite mosaic. Dolomitisation of oolitic limestone is not uncommon. Secondary silicification of dolomitic limestone also occurs. Another feature of this type of limestone is the presence of cracks, sometimes widened to gaps of large size, which may or may not be filled with secondary calcite, quartz or other mineral, e.g. barite, anhydrite; such veins are in the nature of shrinkage-cracks, determined by the volume-contraction of 12.3 per cent. with complete dolomitisation. The association of anhydrite, gypsum, rock-salt etc., with certain dolomitic limestones suggests inorganic origin, i.e. precipitation in land-locked saline water (p. 505).

Types. Cambrian, Durness Limestone, N.W. Highlands of Scotland, Skye etc., pure limestone with sponge remains, partial dolomitisation;¹ Devonian limestone, Devonshire, partial dolomitisation with rhombs picked out with iron oxide;² Permian Magnesian limestone,



DOLOMITIC, OOLITIC AND PISOLITIC LIMESTONES, OOZE AND CHALK

- A. Dolomitic Limestone (Carboniferous), Burslescombe, Somerset [x 42]
 B. Bath Oolite (Bathonian), Farley, nr. Bath. [x 15.]
 C. Osmington Oolite (Corallian), Osmington, Dorset. [x 20.]
 D. Pisolitic Limestone (Silurian), Malvern. [x 9]
 E. Globigerina Ooze, N. Atlantic Ocean, 1,260 fms. [x 23]
 F. Chalk (Cretaceous), Larne, Antrim. [x 35.]

complete dolomitisation, granular dolomite, few organic remains recognisable;³ Triassic Dolomites, Southern Tyrol, massive, unstratified dolomitic limestone, chiefly algal and echinoderm organisms.⁴

Refs. ¹ "Geology N.W. Highlands." *Mem. Geol. Surv. Scot.*, 1907, p. 375.

² E. Wethered, *Quart. Journ. Geol. Soc.*, 48, 1892, p. 377.

³ D. Woolacott, *Quart. Journ. Geol. Soc.*, 67, 1911, p. 312; also *Geol. Mag.*, 1919, p. 452, 485.

⁴ E. W. Skeats, *Quart. Journ. Geol. Soc.*, 61, 1905, p. 97.

General Refs.

"Report of the Coral Reef Committee." *Royal Society*, 1904.

R. C. Wallace, *Cong. Geol. Inter., C.R.*, 12 (1913), 1914, p. 875.

F. M. Van Tuyl, *Iowa Geol. Surv.*, 25, 1914, p. 37.

L. M. Parsons, *Geol. Mag.*, 1918, p. 246.

W. H. Twenhofel, "Treatise on Sedimentation." (Ballière, Tindall and Cox, London), 1932, p. 330, and references cited.

W. A. Tarr, *Journ. Geol.*, 41, No. 3, 1933, p. 268.

L. Cayeux, "Les Roches Sédimentaires de France: Roches Carbonates." (Masson, Paris), 1935.

(B1. a) OOLITIC AND PISOLITIC LIMESTONE.

[Pl. 37 B-D, facing p. 397.]

Def. Oolitic limestone is characterised by spheroidal or ellipsoidal grains of calcium carbonate built up concentrically about a nucleus, e.g. quartz grain, shell fragment.

Pisolitic limestone is a coarse variety of oolitic limestone in which the individual grains attain the size of a pea.

Lith. These are special but commonly developed types of limestone in which the bulk of the rock is composed of spheroidal or ellipsoidal grains of calcium carbonate; such grains exhibit concentric (successive) growths of the carbonate about an organic or inorganic nucleus. The smaller developments, 1 mm. (or less) — 2 mm. in diameter, are the oolites; larger grains, up to the size of a pea or even larger, are the pisolites. Very coarse pisolites are sometimes erroneously termed "grits," e.g. "Pea Grit." Both types are readily recognised by these distinguishing megascopic characters. The oolites and pisolites may be closely packed together, or they may be scattered haphazardly through a finer matrix. Organisms extremely common. Bedding frequent. Colour varies from white in the purest forms of limestone to yellow, brown and red. Secondary calcite and/or silica often noted in the hand-specimen.

Text. Coarse to medium; rough; earthy or rubbly with conspicuous matrix.

Shape. Oolites spheroidal or ellipsoidal; pisolites more irregular, sometimes flattened resembling large nummulites. Detrital constituents SA.

Min. Comp. Al. Quartz, iron-ores and often surprisingly varied accessory mineral suite in the impure types.

Au. Calcite, siderite, dolomite, silica, hematite, limonite. Oolites and pisolites of fine calcareous mud, sometimes crystallised; silicified oolites not uncommon.

Organic Material. Shell-fragments, *foraminifera*, crinoid stems, *polyzoa* etc.

Mech. Comp. Detrital constituents usually of the silt grade. Oolite and pisolite dimensions as above.

Micro. Oolitic and pisolitic limestones, especially the former, are among some of the most striking varieties of sedimentary rocks met with under

the microscope. The oolites themselves first attract attention; examine for nucleus, which may be a detrital quartz grain, shell-fragment or *foraminifer*; in many cases it is represented by a mud particle; sometimes no nucleus is determinable. Concentric layers of carbonate are revealed, often picked out by ferriferous impurity; in some examples radial structure is observed. These oolite grains, together with shell-fragments and free organisms, are set in a fine matrix which, in the purest types, is seen to be composed of a crystalline mosaic of calcite occurring in mutually interferent particles; this matrix is frequently stained with limonite or hematite and spotted with iron oxide. Quartz is common, increasing with the more earthy types. Sometimes much of the centre of the oolite grain is replaced by calcite of the same character as the matrix. The foregoing remarks apply equally to the pisolitic types. Some oolitic limestones exhibit partial, if not complete dolomitisation. In structure, apart from the special developments under discussion, note should be taken of the proportion of oolites or pisolites to matrix; where the latter predominates derivation of the former from pre-existing oolitic or pisolitic rocks may be suggested.

Types. Ordovician, Hirnant Limestone, Bala district, N. Wales, oolites partly replaced by chalcedonic silica and layers picked out with carbon dust;¹ Silurian, Wenlock Limestone, Malvern, oolites scattered in calcareous-argillaceous matrix;² Carboniferous Limestone, Gloucestershire etc., oolitic rock with *Girvanella*;³ Inferior Oolite, Gloucestershire, both oolitic and pisolitic examples, the former with abundant organic remains, the latter ("Pea Grit") characterised by *Girvanella*;⁴ Great Oolite, Malton, Yorkshire, Northamptonshire etc., scattered oolite grains in recrystallised calcite matrix;⁵ also Bath Oolite (Great Oolite), Bath, Somerset, compact oolitic type;⁶ Corallian, Osmington Oolite, a perfect example of a closely packed, pure oolite;⁷ Portlandian, Portland Oolite, Portland, Dorset.⁸

Refs. ¹ L. W. Fulcher, *Geol. Mag.*, 1892, p. 114.

^{2, 5, 6} Author's observations.

³ E. Wethered, *Quart. Journ. Geol. Soc.*, 46, 1890, p. 271.

⁴ E. Wethered, *op. cit.*, p. 274.

⁷ J. H. Blake and W. H. Hudleston, *Quart. Journ. Geol. Soc.*, 33, 1877, p. 265; E. Wethered, *op. cit.*, p. 278; A. Strahan, "Geology of Isle of Purbeck etc." *Mem. Geol. Surv.*, 1898, p. 37.

⁸ G. F. Harris, *Proc. Geol. Assoc.*, 14, 1895, p. 72.

General Refs.

J. J. H. Teall, "Jurassic Rocks of Britain." *Mem. Geol. Surv.*, 4, 1894.

F. M. Van Tuyl, *Journ. Geol.*, 24, 1916, p. 792.

W. H. Butcher, *Journ. Geol.*, 26, 1918, p. 593.

G. W. Tyrrell, "Principles of Petrology." (Methuen, London), 1926, p. 227.

(Bi. 4) **ABYSSAL OOZE (CALCAREOUS).** [Pl. 37 E, facing p. 397.]

Def. Ooze (calcareous) is a soft, incoherent deep-sea deposit composed for the most part of the hard parts of micro-organisms such as foraminifera.

Lith. Under this heading is included all deep-sea oozes of predominantly calcareous character. They are in the main composed of the hard parts of free-swimming pelagic organisms such as *foraminifera*. The two important examples are Globigerina Ooze and Pteropod Ooze.

Dredged samples (e.g. Challenger Expedition) are white to buff-coloured when dry and have the appearance of very fine powder. The organisms are usually too minute to be seen with the naked eye.

Text. Exceedingly fine, homogeneous, "soapy."

Shape. Detrital particles, when present, A.

Min. Comp. *Al.* Felspar, augite, olivine, hornblende, quartz, magnetite, volcanic glass, rock-fragments etc.

Au. Calcium carbonate, silica, magnesite, traces of phosphate, sulphate.

Mech. Comp. Detrital and other inorganic particles <0.01 mm. but highly variable.

Micro. Globigerina ooze is composed principally of the tests of *globigerina* and other *foraminifera*, usually with a small proportion of siliceous organisms, e.g. *radiolaria*, *diatoms*. In addition characteristic disc-like bodies termed *coccoliths* are observed; these are calcareous parts of certain minute planktonic *algæ* (*coccolithophoridae*). Another form of similar origin is the *rhabdolith*, a long slender T-shaped body, not unlike a sponge spicule. Organic matter makes up the bulk of the fine washings of this ooze, though the mineral constituents are normally quite conspicuous, constituting from 3 to 4 per cent. The inorganic matter resembles the abyssal red clay (see A3, 5, p. 382). Pteropod ooze is composed principally of *pteropod* shells and *heteropod* (pelagic gasteropods), together with *foraminifera* and a small percentage of siliceous organisms. This type of ooze is much more variable in character than the globigerina ooze, though there is about the same amount of mineral matter; *coccoliths* and *rhabdoliths* are also found. Both the pteropod and heteropod shells are very delicate and exhibit beautiful forms; much broken and fragmental material is characteristic. Samples relieved of the fine calcareous mud by careful washing are best studied with a binocular microscope, using dark-ground illumination.

Types. Globigerina and Pteropod Ooze, Challenger Expedition.¹

Ref. ¹ J. Murray and A. F. Renard, "Deep Sea Deposits." *Challenger Report*, 1891.

(B1. 5) **CHALK.**

[Pl. 37 F, facing p. 397.]

Def. A fine textured foraminiferal limestone, substantially pure calcium carbonate, of Cretaceous age, as developed in the British Isles and North-West Europe.

Lith. An exceedingly pure form of limestone (calcium carbonate) varying from soft, almost incoherent material to compact, hard rock. White, yellow to grey in colour, the latter implying some admixture of clay material; strongly glauconitic varieties are greenish-grey. Usually homogeneous and well stratified, but bedding not apparent in small specimens. Megascopic organisms are mainly molluscan fragments, especially parts of *Inoceramus*; many other fossils, however, are characteristic, often beautifully preserved. Calcite veins observed in the harder varieties. Flint nodules and marcasite concretions common at certain horizons. Black staining, dentritic patterning, usually on joint-surfaces, due to manganese oxide.

Text. Fine, compact or friable.

Shape. Detrital particles A to SA. Quartz often well rounded.

Min. Comp. *Al.* Rare. Quartz, ilmenite, tourmaline, zircon, staurolite, locally chromite (p. 266).

Au. Calcareous mud, secondary silica, limonite, glauconite.

Mech. Comp. Chalk particles are exceedingly fine in grade and remain suspended in water for considerable time. Detrital grains usually <0.01 mm.

Micro. Hard chalk is best studied by means of thin sections in addition to its investigation in the form of powdered material. The softer varieties are examined as incoherent rocks and may with advantage be washed free of much of the finest mud. For inorganic components the soluble carbonate should be eliminated with acid and the residue segregated. Microscopical examination of chalk shows that it is made up partly of micro-organisms, mainly of very fine calcareous matter and, in the impure varieties, of clay-substance and detrital minerals; the latter are normally scanty. Micro-organisms include *foraminifera*, especially chambers of *globigerina*, also cells and spikes of planktonic algæ known respectively as *coccoliths* and *rhabdoliths* (p. 399), sponge spicules and less commonly *radiolarian* tests. The fine white mud may be due to disintegrated fossil shells or possibly to precipitation from solution. Glauconite frequently fills the chambers of the *foraminifera* present, or otherwise preserves original structures; its partial alteration to limonite is often observed. Other infilling material may be calcite, in well crystallised mosaic, or chalcedonic silica.

Types. Cretaceous: Lower Chalk, Wiltshire, Dorset etc., "Chloritic Marl," a sandy, glauconitic variety;¹ Chalk Marl, with clay material;¹ "Belemnite Marl," a soft grey chalk with belemnites (*Actinocamax plenus*) etc.;² "Totternhoe Stone," dark grey chalk with green-coated nodules (base) and abundant shell-fragments up to 60 or 70 per cent. of the rock;³ Middle Chalk, white, nodular, rough or lumpy; "Melborne Rock," hard, nodular chalk;⁴ Upper Chalk with flints, white, powdery, nodular or in layers.⁵ (N.B.—The so-called "Red Chalk" of Hunstanton, Norfolk, is of Selbornian age, and consists of an argillaceous limestone containing abundant red oxide of iron.)^{6, 7}

Refs. ¹ W. Hill, "Cretaceous Rocks of Britain." *Mem. Geol. Surv.*, 2, 1903, chs. xxii, xxiii, xliii, also 3, 1904, ch. xxii.

² W. Hill, *Quart. Journ. Geol. Soc.*, 44, 1888, p. 320.

³ A. J. Jukes-Browne, "Stratigraphical Geology." (Stanford, London), 1912, p. 504.

⁴ W. Hill and A. J. Jukes-Browne, *Quart. Journ. Geol. Soc.*, 42, 1886, p. 216.

⁵ Author's observations.

⁶ W. Hill, *op. cit.*, 1, 1900, p. 345.

⁷ R. H. Rastall, *Geol. Mag.*, 67, 1930, p. 436.

General Refs.

A. J. Jukes-Browne, *Proc. Yorks. Geol. Soc.*, 12, 1895, p. 385.

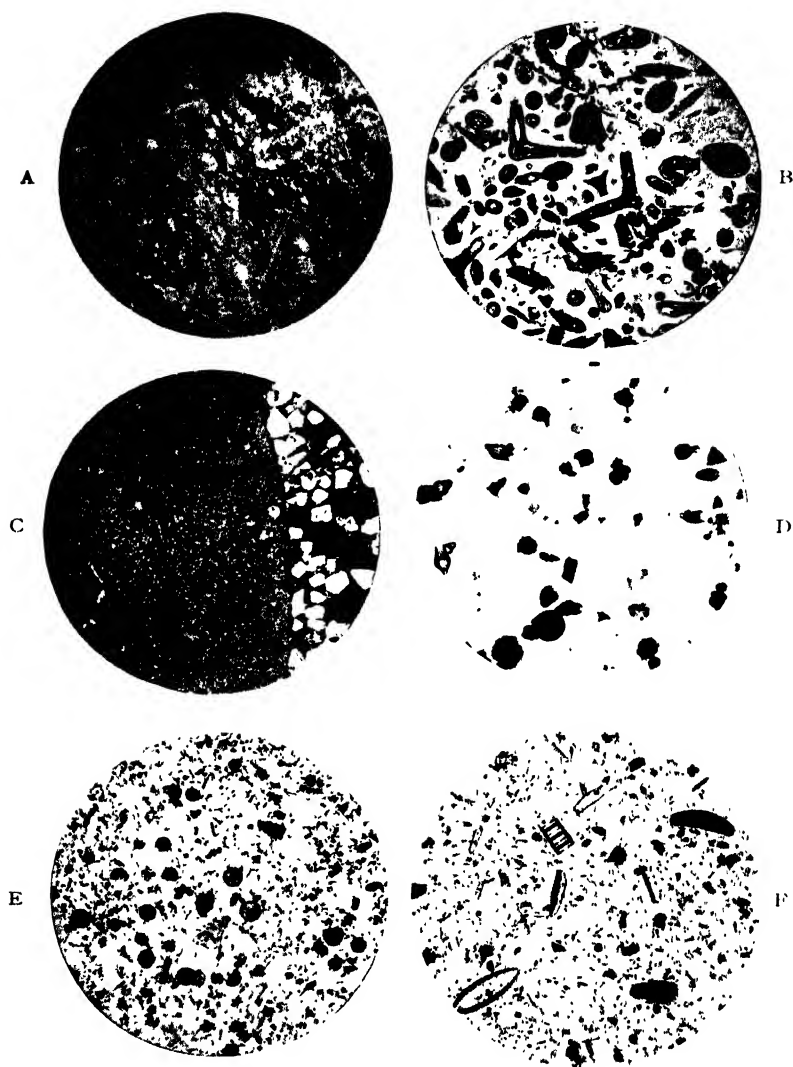
W. Hume, *Quart. Journ. Geol. Soc.*, 53, 1897, p. 568.

W. A. Tarr, *Geol. Mag.*, 62, 1925, p. 252.

I. C. Double, *Journ. Roy. Micros. Soc.*, 1927-8.

L. Cayeux, "Les Roches Sédimentaires de France: Roches Carbonates." (Masson, Paris), 1935.

(B2) SILICEOUS DEPOSITS.—This division includes consolidated rocks such as chert and flint, the abyssal oozes depending mainly on the accumulation of organisms such as *radiolaria*, diatoms and sponge skeletons and the curious



CHERT, FLINT, SILICEOUS OOZE AND DIATOMITE.

- A Radiolarian Chert (Ordovician), Mullion Is., Cornwall. [x 23.]
 B Portland Chert (Portlandian), Swanage, Dorset. [x 15.]
 C Flint, pebble in sandstone (Eocene), Hertfordshire "Pudding Stone"*. [x 15.]
 D Radiolarian Ooze, S. Pacific, 2,425 fms. [x 25.]
 E. Diatomaceous Ooze, Indian Ocean, 1,950 fms. [x 45.]
 F. Diatomite, Loch Cuithir, Skye, N.B. [x 50.]

[*Crossed Nicols.]

To face page 401.

PLATE 38.

"silica earth" deposits, likewise of organic origin. In the case of chert and flint it is admitted that the entirely organic origin of these deposits is open to question; silica derived from chemical reaction may and often does play an important part in their formation (p. 425). For the most part, however, these deposits exhibit so much definitely identifiable organic matter that its predominating influence is seldom in doubt. The following types are recognised:—

(B2. 1) Chert and Flint (p. 401).

(B2. 2) Abyssal Ooze (p. 402).

(B2. 3) Siliceous Earth (p. 403).

(B2. 1) **CHERT AND FLINT.***

[Pl. 38 A-C, facing p. 401.]

Def. Chert is a compact cryptocrystalline rock composed essentially of chalcedonic silica and microcrystalline quartz and characterised by a splintery fracture. The type is not restricted to any particular stratigraphical horizon. Flint is similar to chert in composition, but is more dense and normally exhibits much less microcrystalline quartz, except in weathered examples. Flint is usually restricted in Britain to the Cretaceous (Chalk) developments and to its occurrence in deposits derived therefrom; it is characterised by a marked conchoidal fracture.

Lith. The difference between chert and flint is probably more apparent than real and to some extent is a matter of nomenclature. Both rocks are essentially pure developments of chalcedonic silica occurring in the form of nodules, concretions or bedded layers in calcareous deposits such as limestone. In British stratigraphy the term "chert" applies for the most part to such rocks present in pre-Chalk horizons; flint is restricted to the real Chalk occurrences and to those rudaceous deposits derived therefrom. In external appearance both chert and flint are very similar when fresh, though the former has a more decided splintery fracture, the latter a conchoidal fracture and a tendency to exhibit the complimentary "bulb of percussion" (unlike chert). When fresh, both flint and chert may be blue-grey or indigo in colour; weathering and exposure to atmospheric conditions bring about obvious changes both in colour and appearance (patination). Chert often assumes a "sugary" appearance; flint, a worn, pale-coloured porcellaneous aspect. Chert is often traversed by a network of cracks filled with secondary silica and stained with limonite or hematite; flint is less commonly susceptible to these developments. The interior of a chert nodule is usually solid, often a fossil-shell nucleus or aggregate of fossil particles; the interior of a flint, on the other hand, may be quite hollow and from it a siliceous powder, full of sponge spicules etc., may often be obtained.

Text. Extremely fine, smooth; rough on weathered surface.

Shape. As nodules or concretions, both chert and flint assume diverse shapes, often occurring in most fantastic forms.

Min. Comp. Silica, mainly chalcedony; in flint occasionally opaline silica. Limonite staining.

* Only in part referable to organic origin: see p. 425.

Micro. The microscopical examination of chert depends largely on the age of the material and on its condition as regards weathering. Some varieties, i.e. Portland Chert (Upper Jurassic), as with flint from the Upper Chalk, are almost optically inert and very little, save certain ill-defined organic remains, can be made out. In most cases, however, some degree of crystallisation or cryptocrystalline structure can be ascertained, especially in cherts. When well preserved, the spherical tests of *radiolaria*, or characteristic sponge spicules, are easily diagnosed, but in many so-called radiolarian cherts, the dominant organism is only represented by a blurred spherical structure which has to be taken very much on trust. Every stage between the inert chalcedonic silica, the faint reaction between crossed nicols, to the fine mass of mutually interferent silica particles of brilliant blue-grey or yellow polarisation tints, is discernible in cherts; flint seldom exhibits striking polarisation of phenomena unless markedly weathered. Chert replacement of oolitic or shelly limestone is not uncommon.

Types. Ordovician, Radiolarian Chert, South Scotland;¹ Radiolarian Chert of same age (?), Mullion Island, Cornwall;² Portland Chert, Dorset;³ Upper Cretaceous flint (zone of *Micraster coranguinum*, Upper Chalk), Kent, Cambridgeshire etc.;⁴ Pleistocene gravels from Thames basin: flints showing different degrees of weathering, some with hollow centres, spicule-dust etc.;⁵ G. M. Lees has described some interesting brecciated, banded and replacement cherts from Palestine, the latter type including some remarkable coprolite silicifications.⁶

Refs. ¹ G. J. Hinde, *Ann. Mag. Nat. Hist.*, 6, 1890, p. 41; C. Lapworth, *Geol. Mag.*, 1889, p. 20, 69.

² G. J. Hinde, *Quart. Journ. Geol. Soc.*, 49, 1893, p. 215; H. Fox and J. J. H. Teall, *Quart. Journ. Geol. Soc.*, 49, 1893, p. 211; J. S. Flett and J. B. Hill, "Geology of the Lizard, etc.," *Mem. Geol. Surv.*, 359, 1912, p. 172 and refs. cited.

³ A. Strahan, "Geology of the Isle of Purbeck etc." *Mem. Geol. Surv.*, 1898.

⁴ W. Hill, "Cretaceous Rocks of Britain." *Mem. Geol. Surv.*, 3, 1904.

⁵ Author's observations.

⁶ G. M. Lees, *Proc. Geol. Assoc.*, 39, 1928, p. 445.

General Refs.

W. Hill, *Proc. Geol. Assoc.*, 22, 1911, p. 61.

W. A. Tarr, "Origin of Chert." *Amer. Journ. Sci.*, 44, 1917, p. 413.

W. A. Richardson, *Geol. Mag.*, 1919, p. 535.

W. A. Tarr, "The Origin of Chert and Flint." *Univ. of Missouri Studies*, 1, 1926, p. 2.

W. H. Twenhofel, "Treatise on Sedimentation." (Ballière, Tindall and Cox, London), 1932, p. 519.

W. A. Tarr, "Terminology of Chemical Siliceous Sediments." *Comte. on Sedimentation, Nat. Research Council*, 1936.

(Bz. 2) **ABYSSAL OOZE (SILICEOUS).** [Pl. 38 D and E, facing p. 401.]

Def. Ooze (siliceous) is a soft, incoherent deep-sea deposit composed for the most part of the hard parts of micro-organisms such as radiolaria, diatomacea etc.

Lith. Ooze of siliceous character owes its origin chiefly to radiolarian tests, diatom frustules or sponge spicules, or to a combination of these. Such ooze is seldom pure, but contains admixture of calcareous

organisms (B1. 4, p. 398) and volcanic mud (A3. 1, p. 382). The organisms are not discernible with the naked eye; the material is homogeneous, white, yellow or red in colour and of the consistency of flour. Normally incoherent when dry.

Text. Extremely fine.

Shape. Detrital particles A.

Min. Comp. Al. Quartz, felspar, augite, hornblende, fragments of pumice, magnetic iron ore particles, volcanic rock-fragments etc.

Au. Silica, oxide of iron, calcareous matter, manganese grains etc.

Mech. Comp. Detrital grains 0.15-0.01 mm. or less.

Micro. Under the microscope radiolarian ooze is characterised by the tests or skeletons of these organisms; such skeletons exhibit either lattice-like or reticulate structure and are usually spherical, elongated and with or without spines. These organisms constitute 20 per cent. of the ooze (or more) in typical examples. In the diatom ooze, the siliceous frustules of these vegetable organisms occur in spherical, polygonal, vermiform and other shapes and are associated with calcareous organisms and terrigenous matter. Sponge ooze is a distinctive deposit, composed principally of spicules of varying shape, 3-rayed, 4-rayed, multi-rayed types etc., or as single spicules (monaxonid). Most of these spicules are isotropic between crossed nicols, though with process of time cryptocrystalline silica is noted. The washings from siliceous ooze are made up chiefly of calcareous and siliceous mud in about equal proportions.

Types. Radiolarian Ooze, Pacific and Indian Oceans etc.;¹ Diatom Ooze, Indian Ocean, North Atlantic Ocean etc.;² Sponge Ooze, various deep-sea deposits.³

Ref. ¹ J. Murray and A. F. Renard, "Deep Sea Deposits." *Challenger Report*, 1891, p. 203.

² *Ibid.*, p. 208.

³ Author's observations.

(B2. 3) SILICEOUS EARTH.

[Pl. 38 F, facing p. 401, and Fig. 88, facing p. 404.]

Def. Siliceous Earth is a group term denoting certain types of siliceous deposit, mainly of organic origin, e.g. diatomaceous earth.

Lith. Within this category fall the following rocks:—Radiolarian Earth, Barbados Earth, Diatomaceous Earth (Diatomite=Kieselguhr), Infusorial Earth (of much the same composition as Diatomite). Tripoli, sometimes confused with diatomaceous earth, is a residual product derived from decomposition of siliceous limestone. These earths are fundamentally similar to the oozes (B2. 1), but are formed under different conditions and, moreover, are partially consolidated. For instance, diatomite is produced by the accumulation of diatom frustules in shallow lakes and swamps in contrast to the abyssal environment of the ooze composed of much the same organic material. The earths are usually white, cream, or when impure highly coloured, buff, brown, red; they are homogeneous, porous, pulverulent and have a decidedly earthy "feel" and appearance.

Text. Very fine, powdery, friable, earthy.

Shape. A.

Min. Comp. Al. Usually a conspicuous detrital assemblage varying considerably in nature and quantity. Quartz, iron-ores, zircon, tourmaline, garnet etc.

Au. Silica, limonite, hematite, calcareous matter, carbonaceous matter, manganese etc.

Mech. Comp. Often remarkably uniform, ± 0.05 mm.

Micro. Most examples of these particular rocks can be studied both in thin section and as incoherent materials. Radiolarian earth is composed principally of radiolarian tests (p. 402), diatom frustules and sponge spicules; calcareous organisms are infrequent or absent, but calcareous matter is invariably detected by the "twinkling" reaction. The organisms, as in Barbados Earth, are set in "a felted mass of interlacing fragments of radiolaria and sponge spicules."

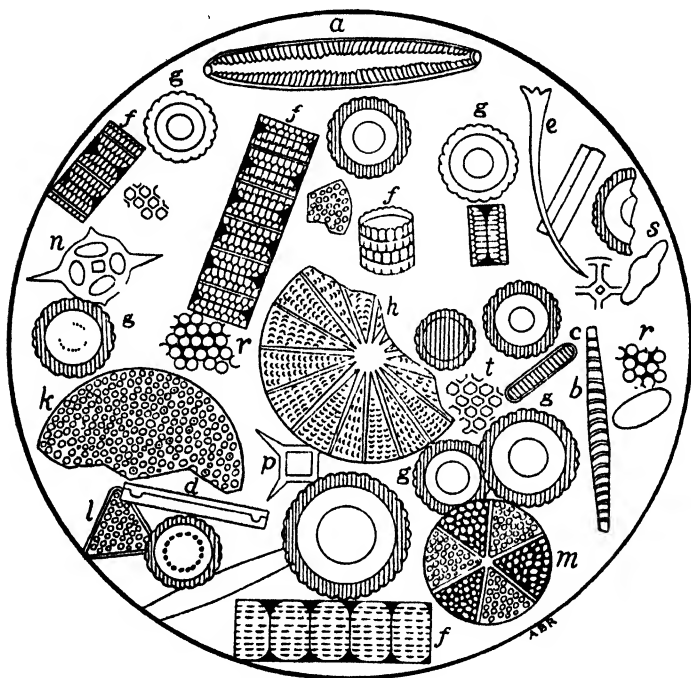
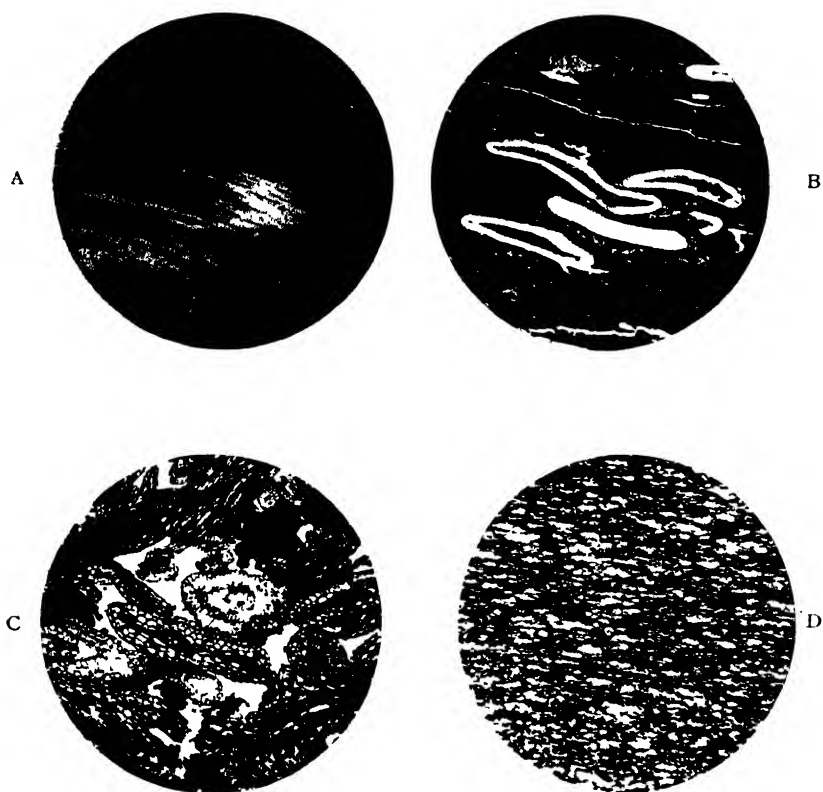


FIG. 88. Infusorial Earth, Richmond, Virginia, U.S.A. (After J. D. Dana.)

a, *Pinnularia perigrina*; b, c, *Odontidium pinnulatum*; d, *Grammatophora marina*; e, *Spongiolithis appendiculata*; f, *Melosira sulcata*; g, transverse view of f; h, *Actinocyclus Ehrenbergii*; i, *Coscinodiscus apiculatus*; j, *Triceratium obtusum*; k, *Actinoplychus undulatus*; l, *Dictyocha crux*; m, *Dictyocha*; n, fragment of *Actinoplychus senarius*; o, *Navicula*; p, fragment of *Coscinodiscus gigas*.

In the case of Diatomite, the principal components are diatom frustules with apparent mineral matter, clay and other micro-organisms. Infusorial Earth is a fine white powder, mainly diatoms, with silica and a little calcite, characterised by its extreme homogeneity. These plant remains assume spherical, cylindrical, cellular and triangular shapes and usually comprise many different recognisable species. In some examples, a few *polycystines* (siliceous *foraminifera*) occur.



LIGNITE AND COAL.

- A. Lignite (Oligocene), Bovey Tracey, Devon. [x 14.]
- B. Spore Coal (Coal Measures), Moira Colliery, Leicestershire. [x 25.]
- C. Halifax Hard Coal (Lanarkian), Deighion, Yorks., with *Lyginopteris oldhamia*. [x 15.]
- D. Torbanite, Moifontein District, S. Africa [x 14.]

Types. Recent and Tertiary Radiolarian Earths, Barbados, Trinidad, B.W.I.;¹ Recent Diatomite, Skye, Aberdeenshire etc., N.B.;² Tertiary, Richmond, Virginia, U.S.A., Infusorial Earth.³

Refs. ¹ A. J. Jukes-Browne and J. B. Harrison, *Quart. Journ. Geol. Soc.*, 48, 1892, p. 174.

² *Mem. Geol. Surv., Spec. Rep. Min. Resources, Gt. Brit.*, 5, 1916, p. 35.

³ J. D. Dana, "Manual of Geology." (American Book Company, New York), 1876, p. 496, Fig. 882.

General Ref.

N. Goodwin, "Bibliography of Diatomaceous Earth." *Chem. Met. Eng.*, 23, 1920, p. 1158.

(B3) FERRUGINOUS DEPOSITS.—Research on sedimentary iron-ores, more especially the bedded iron-ores of England and Wales by A. F. Hallimond,¹ has shown conclusively the dominating influence of chemical reaction and precipitation in the formation of these deposits. For this reason these rocks are more logically considered under the heading of chemically-formed deposits (Group C), (p. 419). On the other hand, due recognition of the important part played by bacteria in the chemical processes and the belief in certain cases that iron deposits are due directly to organic origin of this kind, make it advisable to retain a place in the present scheme under the heading of organically-formed deposits, more especially in view of the fact that considerable research is still in progress to determine the precise nature of the organic reactions known to take place. This is but another instance of the difficulty of fitting all sedimentary rock-types into "water-tight" compartments, not that the author admits either the practice or desirability of so doing in this book.

A. F. Hallimond,² writing on this subject, says, "The role of the 'iron bacteria' in the formation of the iron ores has lately received much attention, but it seems likely that this small group represents only a fraction of the organisms concerned and that the action of the ordinary types of bacteria is of no less significance and of far wider extent . . . the crystalline nature of the rocks as seen in the micro-section rarely offers the suggestion of anything but a purely inorganic reaction. Such a system is, nevertheless, not at variance with the theory of bacterial action. . . . Iron and other inorganic materials may

¹ *Mem. Geol. Surv., Spec. Rep. Min. Resources, Gt. Brit.*, 29, 1925.

² *Op. cit.*, p. 14.

not play a part in the structure of the organism itself, but they will be affected in various ways according to the products yielded by the organism, so that, for example, the reduction of ferric oxide and the production of carbon dioxide in quantity may depend entirely on the existence of suitable organisms which need not themselves be iron-secreting. The insoluble compounds of the inorganic materials are, however, very limited in number, so that the ores precipitated cannot present a chemical or mineralogical variety at all comparable with the variety of organisms that may be concerned. In this way it seems possible to reconcile the uniformity of the ironstones with the probability that their formation is partly or wholly conditioned by bacteria."

Thus, Lake-ore or Bog Iron-ore has been attributed by more than one writer directly to organic process, decomposition of vegetable matter and influence of bacteria and has been discussed under this heading. In this book both are described in conjunction with other sedimentary ferruginous deposits in the category of chemically-formed rocks, for reasons above stated.

(B4) CARBONACEOUS DEPOSITS. — This somewhat heterogeneous group comprises the naturally occurring solid hydrocarbons, the inherent variations and abundant transitional types of which render them difficult to bring within the limits of a few main types. All agree, however, in fundamental biological origin, in which vegetable matter has played a significant part. The pure petrology of these rocks has been conspicuously neglected, save in one or two instances referred to in the sequel. They are none the less all susceptible to petrographical analysis along precise lines of investigation, though much depends on the production of the necessary thin sections, notoriously difficult to achieve in many of the types, *e.g.* coals, asphalts.

No attempt is made here to consider every possible carbonaceous rock encountered in the technology: that would be considerably beyond the scope of this volume. Nor is the fact lost sight of that, in the case of the coals and allied rocks, ultimate structural analysis rests largely on competent palæobotanical knowledge, again outside the province of this book.

On the other hand, carbonaceous rocks have a very definite petrology, at once significant as a study of their mineral composition and of certain factors concerning their genesis. Recent tendencies have shown a desire existing among many geologists to bring such petrology up-to-date and it is hoped that what follows in this connexion will help to clear the ground for further research.

The following subdivisions of the carbonaceous rocks may be made as a provisional basis of discussion :—

- (B4. 1) Peat (p. 407).
- (B4. 2) Lignite (p. 408).
- (B4. 3) Coal and Anthracite (p. 409).
- (B4. 4) Cannel and Torbanite (p. 412).
- (B4. 5) Oil Shale (p. 413).
- (B4. 6) Asphalt, Asphaltic Bitumen and Bituminous Impregnations (p. 414).

(B4. 1) **PEAT.**

Def. Accumulated vegetable matter composed chiefly of moss and bog plants and forming extensive superficial deposits in suitable moist environments.

Lith. Partially carbonised vegetable matter in which much of the latter is still recognisable in the form of plant roots, stems, fibres etc. There is often, however, a fine, earthy, clay-like matrix, very homogeneous in character and only decipherable under the microscope. Colour varies from dark brown to black, while texture and degree of consolidation are very variable. A certain amount of mineral-matter in the form of sand is often visible to the naked eye. Hill or "upland" peat, as it is termed, differs in outward characters from fen-peat, the latter being essentially swamp-muck. Upland peat is more fibrous and spongy and contains much *sphagnum* and other mosses, while tree-trunks and branches may be embedded in it. Fen-peat is more homogeneous, darker in colour and is composed largely of amphibious swamp-plants, *e.g.* sedge, rushes etc. A very crude "stratification" is sometimes apparent in large samples.

Text. Coarse, fibrous, earthy; often compact and clay-like.

Shape. Mineral particles A.

Min. Comp. Mineral particles are chiefly quartz, iron-ores and the more stable accessory species common to neighbouring rocks. In the most compact types, inorganic matter may be less than 3 per cent.

Mech. Comp. Grade-size of mineral particles variable, but often of the sand-grade.

Micro. Peat varies microscopically according to the depth below the uppermost layers from which samples are taken. The superficial material is incoherent when dry and any inorganic matter is easily washed out with water. The rest consists of modern plant material, much fibrous tissue, rootlets etc. With greater depth, samples become more compact and change in character, incipient carbonisation also

being apparent. Relieved of its water, this material is made up largely of a blackish-brown, inert, clay-like substance (humus), a restricted amount of plant-remains and "sand," recognisable from scattered quartz grains (with polarised light). For the most part this form of peat is structureless, the ingredients lying haphazardly, except in the lowest layers, when some degree of parallelism (bedding) may be observed. The inorganic matter is best studied by segregating it from the mass of the rock (p. 77).

Types. Upland peat from the Pennine Hills, England, and from the Grampians, Scotland; Lowland or Fenland peat from Cambridge-shire etc.¹

*Refs.*¹ E. A. N. Arber, "The Natural History of Coal." (University Press, Cambridge), 1912, ch. iv, and refs. cited.

General Refs.

F. W. Clarke, "Data of Geochemistry." *U.S. Geol. Surv., Bull.* 770, 1924, p. 760 and refs. cited.

G. W. Tyrrell, "Principles of Petrology." (Methuen, London), 1926, p. 243.

(B4. 2) **LIGNITE.**

[Pl. 39 A, facing p. 404.]

Def. Lignite is a group term denoting types of coal intermediate between peat and bituminous coal, containing over 20 per cent. of water and usually associated with post-Carboniferous (especially Tertiary) deposits.

Lith. The term "lignite" covers a number of different substances which, in so far as carbonisation is concerned, fall midway between peat and coal (bituminous). Examples are lignite proper, brown coal, pitch and glance coal, jet etc. Such rocks occur in the geologically younger deposits, chiefly Mesozoic and Tertiary, in contradistinction to the bituminous coals of Palæozoic age. The rock is normally compact, with a dull black or brown lustre, these also being the characteristic colours. Composition and external features vary widely. In thin seams it is often intersected with fine vertical or oblique cracks, and splinters readily. More massive material breaks with conchoidal fracture. Plant remains seldom recognisable megascopically. Clusters and aggregates of pyrite common.

Text. Uniform, fine, smooth; in some varieties earthy.

Shape. Mineral particles usually A.

Min. Comp. Quartz, iron-ores (especially pyrite), zircon and other occasional accessories. In some of the Bovey Tracey lignites (Devonshire) detrital minerals derived from the Dartmoor granite and associated rocks have been isolated.

Mech. Comp. Mineral particles variable, but on the whole of fine (silt) grade.

Micro. Thin sections of lignite exhibit much brown, translucent matter for the most part optically inert, though faint birefringent reaction in patches is sometimes discernible. Traces of vegetable structure are frequently noted. Pyrite and limonite staining are common features. The average section tends to be thick and opaque in the centre, though the edges are frequently very thin and this facilitates observations. Gypsum and calcite have both been observed in these rocks. In many examples there is noted a rough parallelism, sometimes distinct lamination, of the chief organic ingredients. The presence of veins and pockets filled with secondary mineral is not uncommon. The inorganic matter is best studied separately as a segregation from the main mass of the rock, by digesting it with suitable solvent (p. 77).

Types. Upper Lias, Whitby, Yorkshire, "Jet," homogeneous, coal-black substance, with resinous lustre and conchoidal fracture, often showing coniferous wood structures under the microscope;¹ Wealden (Wadhurst Clay), Sussex, lignite seams with pyrite, calcite;² Fairlight Clay, lignite associated with siderite etc.;³ Upper Oligocene, Bovey Tracey, Devonshire, typical lignite with *Sequoia* wood, fronds of *Osmunda lignitum*, leaves and seeds of various plants, and conspicuous mineral matter.⁴

Refs. ¹ *Mem. Geol. Surv., Spec. Rep. Min. Resources, Gt. Brit.*, 7, 1918, p. 22.

^{2, 3} Author's observations.

⁴ *Op. cit.*, p. 1; also A. J. Jukes-Browne, "Stratigraphical Geology." (Stanford, London), 1912, p. 578.

General Refs.

E. A. N. Arber, "Natural History of Coal." (University Press, Cambridge), 1912, p. 60, 65, 122.

F. W. Clarke, "Data of Geochemistry." *U.S. Geol. Surv., Bull.* 770, 1924, p. 763, and refs. cited.

(B4. a) **COAL AND ANTHRACITE.** [Pl. 39 B and C, facing p. 404.]

Defn. Coal is a group term denoting black carbonaceous deposits formed from accumulation of vegetable matter subsequently carbonised and consolidated under normal diagenetic conditions. Anthracite is a variety of coal containing less than 10 per cent. volatile matter.

Lith. Under this heading are considered the so-called bituminous coals and anthracite. Both imply, for the most part, considerable geological age (Palæozoic) for their achievement. In composition and degree of carbonisation, bituminous coal may be said to lie between lignite on the one hand and anthracite on the other; but the term cannot be sharply defined, as some coals decidedly "overlap" the lignite types, while transitions to anthracite are common. Anthracite as defined above is essentially a variety of coal containing less than 10 per cent. of volatile matter and over 90 per cent. of carbon. Lithologically, bituminous (or humic) coal presents the appearance of a well stratified, carbonised mass of vegetable matter, some of it discernible as such, much of it compact, homogeneous and void of megascopic structure. Bedding may be thin or thick; sometimes exceedingly fine laminæ are developed. Both texture and lustre are notable, alternating dull and bright bands being characteristic. Coal is always well jointed, yielding roughly rectangular blocks. The presence of pyrite along the bedding planes, on joint-surfaces or in pockets, is common. Anthracite is much harder than ordinary coal, has a somewhat metallic lustre, does not soil the hands and breaks with an irregular, conchoidal fracture.

Considerable difference of opinion exists regarding the nature of the materials composing the coal-substance. As some of these are given particular names and can be recognised megascopically, they may conveniently be mentioned here, though to some extent this anticipates remarks under "microscopical observations." The "*Fusain*" component is the soft, powdery, charcoal-like material detected along some of the bedding planes. In contrast to this is the compact "*Bright Coal*" and "*Dull or Matt Coal*"; to the latter M. C. Stopes has given the name "*Durain*."¹ The bright coal (sometimes known as "*Glance Coal*") much resembles jet. The dull coal is grey-black, lustreless and rough. There are, further, two

¹ *Proc. Roy. Soc. London, B*, 90, 1919, p. 470.

varieties of bright coal, "*Clarain*" and "*Vitrain*"; the former exhibits smooth surface and glossy lustre, with fine lamination; it also shows intercalations of durain. Vitrain, on the other hand, is homogeneous, with brilliant lustre, conchoidal fracture, presenting clean-cut boundaries to the associated substances; it is supposed to represent "hardened colloidal carbonaceous jelly resulting from complete decomposition of plant matter."¹

C. S. Fox has had occasion to examine these coal substances in really thin sections under the microscope and has reached certain conclusions which differ in fundamental respects from the views just summarised.² These are more appropriately discussed below.

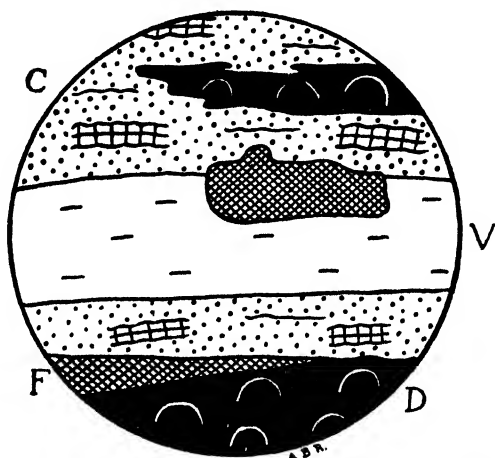


FIG. 89. Coal Constituents; c, clarain; d, durain; f, fusain; v, vitrain. (After M. C. Stopes, *Proc. Roy. Soc. London*, B, xc, 1917-19, p. 483.)

Text. Variable; fine and compact, to coarse, powdery, earthy in coal; fine, smooth, resinous in anthracite.

Shape. Mineral particles A. Isolated particles of coal-substance also A.

Min. Comp. Al. Quartz, tourmaline, garnet, zircon, rutile, metallic ores etc.; more rarely sulphides and native elements (p. 78).

Au. Calcite, siderite, pyrite, limonite, silica, ankerite³ etc., in addition to the various forms of carbonaceous matter.

Mech. Comp. Detrital constituents usually of fine grade.

Micro. The essential factor to the study of coal, of whatever kind, is a *really thin, translucent, if not transparent, section*; this requires considerable skill to prepare and, in point of fact, the best sections available have so far been produced by one laboratory whose method has not been divulged. C. S. Fox, working on slides from this laboratory, has examined the so-called substances clarain, vitrain, durain and fusain derived from certain British coals (both in parallel and trans-

¹ G. W. Tyrrell, "Principles of Petrology." (Methuen, London), 1926, p. 245.

² *Mining Mag.*, 36, 1927, p. 16.

³ T. Crook, *Mineral. Mag.*, 16, 1912, p. 219.

verse sections), and writes as follows:—¹ "Except for the slides of so-called fusain, which obviously contain much inorganic matter—pyrite, calcite and siderite—as well as what appears to be free carbon, the matrix, where thin enough to be translucent, is composed of the madder-red substance. In the sections cut vertical to the laminæ this substance shows very faint pleochroism in plane polarised light and decided straight extinction between crossed nicols, and again behaves as though the whole were part of a single crystal." He also found in all the slides sections of the resinous wall of spores of red or gold colour, with bright, gold, translucent microspores packed in along the laminæ. He further says, "In all the slides cut parallel to the bedding the translucent madder-red material behaves as an isotropic substance in polarised light . . . (with) a doubtful approach to a uniaxial figure." He believes that the madder-red material is the same in all slides examined and concludes that "There is no doubt whatsoever that the substance called vitrain is the same as clarain." "In short, the coal constituents are: (a) Vitro-clarain or pure bright coal as the chief component; (b) sporangia cases and spores and other resinous bodies as modifying constituents; (c) mineral charcoal or fusain as a peculiar subsidiary constituent, evidently marking a 'break' in the normal process of coal accumulation; and (d) the primary inorganic matter of the original plant as well as the secondary inorganic material which has been deposited in the coal, in joints and cracks and other channels for infiltrating waters." Every student of coal, whether from a palæobotanical or petrological standpoint, should read this paper carefully. The author's observations serve to confirm much of what that investigator has stated. C. S. Fox does not, however, touch on the detrital constituents of these rocks, which are no less interesting and significant; for methods of study, see p. 77. Finally, the work of A. Stuart may be quoted on South Welsh anthracite; he "has been able to distinguish bright bands of splendid lustre and structureless character, corresponding to vitrain; black bands of fairly bright coal with waxy lustre, and dark black 'charcoal' bands, representing fusain."²

Types. Palæozoic, Coal Measures, Warwickshire, Lancashire and Yorkshire coalfields etc.;³ anthracite from South Wales etc.⁴ (N.B.—C. S. Fox's slides were of coal from Exhall, Warwickshire, and from the Trencherbone coal, Atherton, Lancashire.)

¹ *Op. cit.*, p. 20. See also H. B. Milner, *Mining Mag.*, 36, 1927, p. 93.

Refs. ² *Geol. Mag.*, 61, 1924, p. 360, quoted from G. W. Tyrrell, *op. cit.*, p. 247.

³ A. J. Jukes-Browne, "Stratigraphical Geology." (Stanford, London) 1912, p. 294.

⁴ A. Stuart, *op. cit.*

General Refs.

E. A. N. Arber, "Natural History of Coal." (University Press, Cambridge). 1912.

D. White and R. Thiessen, "The Origin of Coal." *U.S. Bur. Mines*, 38, 1913.

M. C. Stopes and R. V. Wheeler, "Monograph on the Constitution of Coal." *Dept. Sci. and Indust. Research*, London, 1918.

R. Thiessen, *Journ. Geol.*, 28, 1920, p. 185. (See also paper by C. S. Fox (above) for review of literature dealing with microscopy of coal.)

- F. W. Clarke, "Data of Geochemistry." *U.S. Geol. Surv., Bull.* 770, 1924, p. 768 and refs. cited.
 R. Potonié, "Einführung in die allgemeine Kohlenpetrographie." Berlin, 1924.
 R. Thiessen and G. C. Sprunk, "Microscopic and Petrographic Studies of Certain American Coals." *U.S. Bur. of Mines, Tech. Paper* 564, 1935.

(B4. 4) **CANNEL AND TORBANITE.** [Pl. 39 D, facing p. 404.]

Def's. Cannel is a dull, lustreless variety of coal characterised by a particular conchoidal fracture. It is rich in volatile matter.

Torbanite is technically a variety of oil shale, named originally from Torbane Hill (Midlothian area, Scotland); it has also been described as "Boghead Cannel" and has been legally defined as "coal" (see ref. 3 (p. 245) on p. 413 opposite).

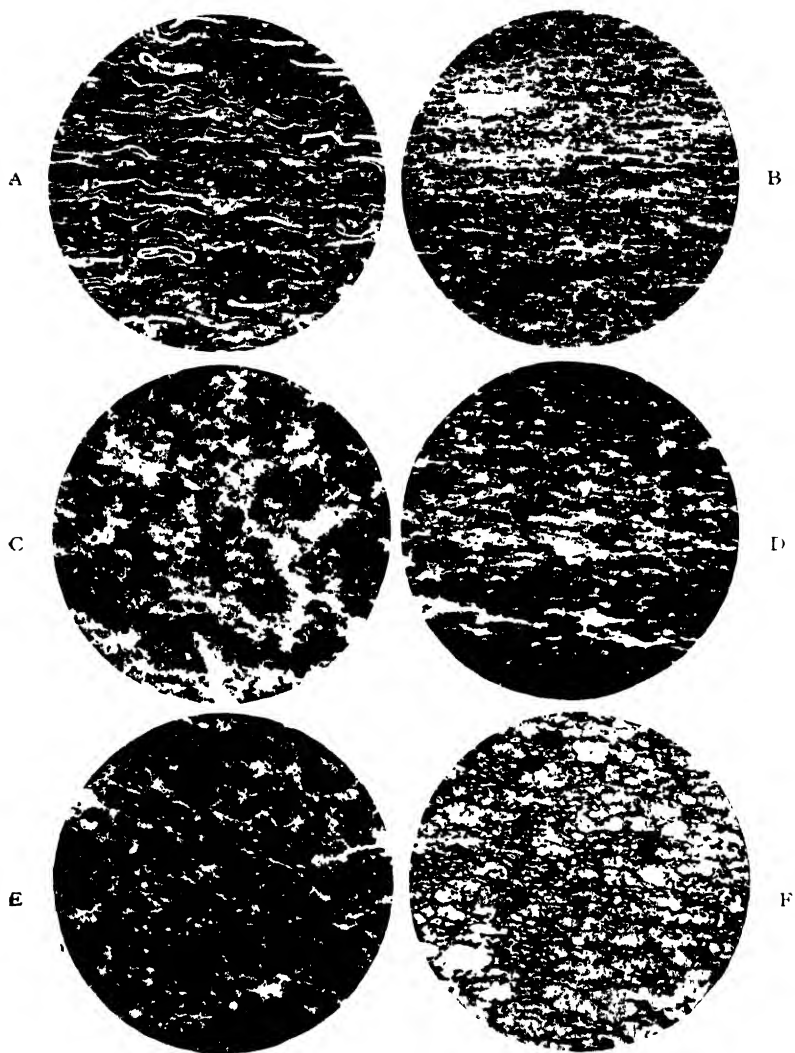
Lith. The distinction between cannel and torbanite on the one hand, and between torbanite and oil shale (B4. 5) on the other, is by no means an easy one to make; practically every gradation exists between them. The essential property of cannel is its dull, lustreless character, conchoidal fracture and ability to burn readily with a bright flame, since it contains considerable amounts of volatile matter. Torbanite is similar in external appearance; it also contains a high percentage of volatile matter but is characterised by peculiar spore or algal structures (see below). Both cannel and torbanite (to which latter the name "*boghead cannel*" is often given) contain considerable mineral matter; when this exceeds the carbonaceous matter, the rock automatically passes into the category of oil shale. Torbanite is definitely considered to be an oil shale by some authors.¹ Bedding may or may not be apparent in these types; usually, if developed at all, it is on a large scale. Jointing is common and both types tend to break into roughly rectangular blocks.

Text. Both cannel and torbanite are close-grained, fine, compact and homogeneous; the former often has a pitch-like texture, the latter is somewhat resinous.

Min. Comp. Little is known as to the nature of the mineral components of these rocks; detrital minerals are few and uninteresting in samples examined by the author. The coal-substance has been regarded by R. Potonié as "*sapropel*," a solidified jelly-like carbonaceous slime.

Micro. Under the microscope, slides of cannel and torbanite exhibit beautiful vegetable structures, differing considerably from bituminous coals, but showing affinities with the richer types of oil shale. Thin sections of cannel exhibit a number of plant-spores set haphazardly in a translucent, more or less optically inert, structureless mass. Torbanite contains an abundance of yellow, oval bodies considered to be spores by some authorities, *algæ* by others. Cannel is stated to be composed largely of the spores of *Lycopods*; torbanite, of gelatinous *algæ* known as *Pila* and *Reinshia*; actually the true nature of these organic remains is the subject of considerable controversy. For the rest, both coals indicate the presence of inorganic matter, *e.g.* calcite, pyrite, limonite, quartz, but the substances characteristic of bituminous coals seem to be absent, indicating a totally different origin for cannel and torbanite, or at least a different mother-substance; on this most investigators are agreed, but more research is required before these types can be said to be defined petrologically.

Types. Cannel from the Coal Measures of North Staffordshire, Yorkshire, Flintshire etc.;² Boghead or Torbanite from Torbane Hill,



OIL-SHALE.

- A. "Tasmanite," Tasmania. [x 25.]
 B. Oil-shale (Carboniferous), Oakbank, Linlithgow, N.B. [x 25.]
 C. do. (Kimmeridgian), Kimmeridge, Dorset, || bedding [x 15.]
 D. do. do. do. do. ⊥ bedding. [x 15.]
 E. "Kugger-site" (Ordovician), Esthonia. [x 40.]
 F. Oil-shale, Blue Mountains, New Zealand. [x 22.]

Scotland ("Torbane Hill Mineral, West Lothian");³ "Tasmanite," Tasmania, "spore coal."⁴

- Refs.* ¹ A. Holmes, "Nomenclature of Petrology." (Murby, London), 1920, p. 227.
² *Mem. Geol. Surv., Spec. Rep. Min. Resources, Gt. Brit.*, 7, 1918, p. 46.
³ "Oil Shales of the Lothians." *Mem. Geol. Surv.*, 2nd ed., 1912, p. 159; 3rd ed., 1927, p. 1, 242 etc.; H. R. J. Conacher, *Trans. Geol. Soc. Glasgow*, 16, 1917, p. 164.
⁴ R. Potonié, *op. cit. infra.*, p. 28.

General Refs.

- E. A. N. Arber, "Natural History of Coal." (University Press, Cambridge), 1912.
 R. Potonié, "Allgemeine Petrographie der 'Olschiefer' und ihrer Verwandten." Berlin, 1928.
 R. Thiessen, "Origin of Boghead Coals." *U.S. Geol. Surv., Prof. Paper*, 132, 1925.

(B4. 5) **OIL SHALE.**

[Pl. 40, facing p. 413.]

Def. A particular type of shale, of black or brown colour, containing a substance known as "kerogen," which yields crude petroleum on destructive distillation.

Lith. Oil shale, if the exceedingly rich types approximating cannel and torbanite be excluded, normally combines the essentials of ordinary sedimentary shale (A3. 5, p. 386) plus a varying amount of carbonaceous matter which, on destructive distillation, yields a form of petroleum. It differs considerably in megascopic characters from either cannel or torbanite. Usually black, brown or greyish-brown in colour; distinct lamination, often finely developed. Many varieties have a leathery appearance and when cut with a knife peel in the form of curved flakes, which may burn with a luminous flame.

Text. Fine, smooth, often polished; some varieties resinous.

Shape. Detrital particles A to SA.

Min. Comp. *Al.* As for shale (A3. 5, p. 386).

Au. Carbonaceous matter of distinctive character (see below) in addition to carbonate of lime, silica, limonite and clay-substance. Part of the carbonaceous matter from which oil is distilled is known as "kerogen."

Micro. Oil shale should be studied petrologically in the same way as ordinary shale, i.e. by parallel and transverse sections. Under the microscope the essentially laminated feature is seldom in doubt, while quartz, iron-ores and secondary minerals such as limonite and calcite, also pyrite, are easily diagnosed. The organic matter, however, presents a more difficult problem. According to some observers there are four distinct types of material: the "ulmic" binder or ground-mass, spore and pollen exines, cuticles and cuticular secretions, and *algæ*; the latter approximate similar bodies found in spore coals (B4. 4). With approach to cannel or boghead types, the organic matter becomes more pronounced and includes fronds, filaments of *algæ*, *fungi* fragments etc. Some measure of parallel orientation of the organic material is observed in these shales, but the inorganic impurities are on the whole irregularly distributed. In some varieties, crystalline calcite occurs as secondary infillings of plant spores or replacing algal structures.

Types. Oil shale from the Lothians, Scotland, type material;¹ Kimmeridge oil shale, Dorset, a variable type with calcite, pyrite and a distinctive pyritised crinoid, *Saccocoma*, visible to the naked eye on bedding planes;² Tertiary oil shale from Green River, Utah, with crustacean material, cuticular spores and resins.³

Refs.¹ "Oil Shales of the Lothians." *Mem. Geol. Surv.*, 2nd ed., 1912, and 3rd ed., 1927; H. R. J. Conacher, *Trans. Geol. Soc., Glasgow*, 15, 1917, p. 161.

² *Mem. Geol. Surv., Spec. Rep. Min. Resources, Gt. Brit.* 7, 1918. (For significance of *Saccocoma*, see *Geol. Surv., Gt. Brit., Summary of Progress*, 1910, p. 62 etc.)

³ W. H. Twenhofel, "Treatise on Sedimentation." (Ballière, Tindall and Cox, London), 1926, p. 297 and refs. cited; also *Fig. 32*.

General Refs.

T. Stadnichenko and D. White, *Bull. Amer. Assoc. Pet. Geol.*, 10, 1926, p. 860.

R. Potonié, "Allgemeine Petrographie der 'Olschiefer' und ihrer Verwandten." Berlin, 1928.

(B4. •) ASPHALT, ASPHALTIC BITUMEN AND BITUMINOUS IMPREGNATIONS.

[*Fig. 90, p. 416, Pl. 41, facing p. 416 and Pl. 48-51, facing p. 541, 542, 544 and 546 respectively.*]

Def's. The nomenclature of "asphalt" and "bitumen" is notoriously conflicting. Certain British Standard definitions [v. B.S.S.596—1935] are here quoted, but they are based essentially on industrial interpretation.

Bitumen denotes "mixtures of hydrocarbons of natural or pyrogenous origin or combinations of both (frequently accompanied by their non-metallic derivatives) which can be gaseous, liquid, semi-solid or solid, and which are completely soluble in carbon disulphide."

Asphaltic bitumen is "natural or naturally occurring bitumen, or bitumen prepared from natural hydrocarbons or from derivatives of natural hydrocarbons by distillation or oxidation or cracking; solid or viscous, containing a low percentage of volatile products, possessing characteristic agglomerating properties, and substantially soluble in carbon disulphide."

Asphalt denotes "natural or mechanical mixtures in which the asphaltic bitumen is associated with inert mineral matter."

"Lake asphalt is an asphalt which, as found in nature, is in a condition of flow or fluidity."

Natural asphalt rock (or rock asphalt) denotes a "naturally occurring, consolidated, calcareous rock impregnated with bitumen exclusively by a natural process; the term shall exclude all other types of rock such as result from sporadic bitumen in any mode of occurrence in non-bituminous limestone or in a limestone of low-grade impregnation, non-bituminous limestones and artificial mixtures thereof with bitumen of any source and description."

Lith. In this category are placed those peculiar forms of solid hydrocarbon ranging from the purest bitumen deposit, to rocks in which only a comparatively small percentage of bitumen occurs as impregnating material. While this course may be conveniently adopted as a basis of petrological description, from chemical and physical standpoints the materials vary widely and can hardly be said to come under any one heading. It will further be obvious that, in the case of low percentage impregnation-types, bitumen-bearing rocks constitute hybrids of mechanically- and organically-formed deposits, which

might at first glance seem to justify their segregation from the purely carbonaceous deposits; but with types in which the organic material may vary from 1 to 97 per cent., it is difficult to draw any sharp line of division and as the majority is indeed highly carbonaceous, there is little reason for defining a separate hybrid group. At the outset it is emphasised from the above definitions that the term "bitumen" is really a group-name to include most of the naturally occurring hydrocarbons, of which "asphalt" is a particular solid or semi-solid variety; "bitumen" is, however, often used colloquially as synonymous with "asphalt," hence much of the prevalent confusion in nomenclature.

Megascopically, pure, native bitumen is characterised by a black colour, glossy appearance, definite fracture and brittle tendencies; with the approach to semi-solid forms, fracture and brittle tendencies are obliterated, also the colour often changes to shades of dark brown; where the bitumen occurs as an impregnation, *e.g.* in limestones or sandstones, it tends to be very finely disseminated and to play much the same role as an infiltrating mineral solution.

The following different types of these rocks may be recognised:— native asphalt, containing less than 10 per cent. of mineral matter; native asphalt occurring in all proportions as impregnating material or sediments; so-called "asphaltites" which include gilsonite, glance pitch and grahamite (the "manjak" of Barbados belongs here); and asphaltic pyrobitumens, including albertite, elaterite *etc.*, which, with increasing mineral matter, pass into asphaltic shales, finally bridging the gap between asphalt as such and oil shales.

Text. Mineral particles when excessive may produce a gritty texture, but in the purest forms asphalt is very smooth, homogeneous and pitch-like.

Shape. Detrital particles A to SA.

Min. Comp. Excluding bituminous rocks, the only minerals discernible under the microscope in native asphalts *etc.*, are stable detrital species normal to the environments concerned. The hydrocarbon behaves as a dense, complex matrix, void of any crystalline properties. Most of the asphaltic limestones ("rock asphalts") from well-known localities, *e.g.* Seyssel and Pyrimont, St. Jean de Maruéjols (Gard), France; Neuchatel and Val de Travers, Switzerland; Ragusa, Sicily; Scafa, Italy; Voerwohle, Germany, yield restricted though distinctive detrital (heavy) mineral residues.

Micro. The method of studying these rocks depends largely on their nature, purity and degree of solidification. Where it is possible to cut thin sections, these should always be employed; this applies to solid native asphalts and asphaltites, equally to all impregnated rocks. Detrital minerals are best investigated as concentrates segregated by dissolving out the hydrocarbon (p. 80). [N.B.—In the preparation of the thin section, the greatest care must be taken to avoid heating the material sufficiently to cause it to flux with the mountant, or otherwise to develop artificial structure.] Under the microscope asphalt exhibits a brown translucency where sufficiently thin; but not many optical reactions can be obtained, nor in most cases can any structure in the hydrocarbon be made out. Where mineral matter is present, the quartz grains are easily picked out by polarised light; sometimes incident light observations aid the discrimination of organic and inorganic matter. Many examples of asphalt which, from megascopic observation, seem remarkably pure, are found to contain abundant quartz and other minerals on closer analysis.

The most interesting and profitable research, however, is that on the impregnated rocks where, given a skilfully prepared section, the manner and degree of impregnation of a normal sedimentary rock can be studied. In these cases much depends on the rock itself. With sandstones, the bituminous material is seen to act very much in the nature of a cement, filling voids and mineral-interstices, or where bedding is manifest, "pushing" its way along the planes,

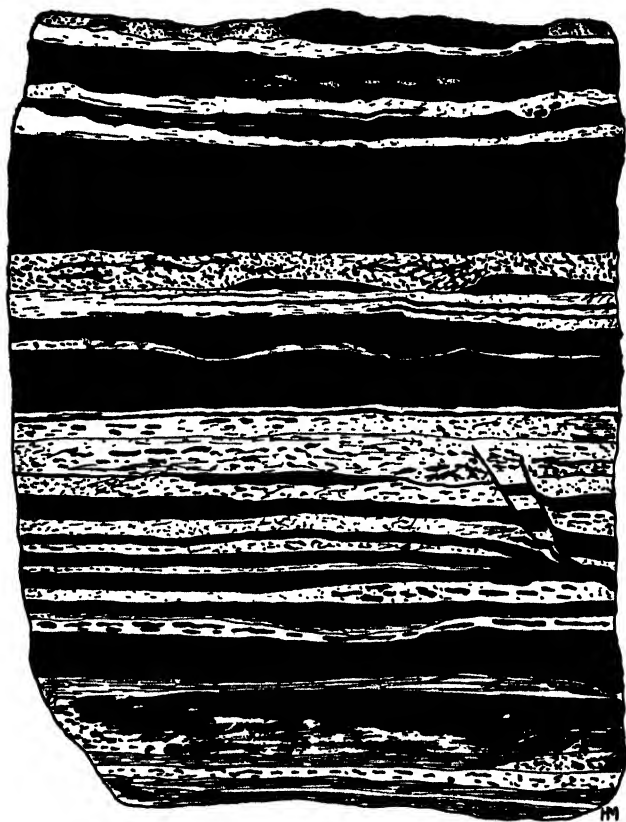
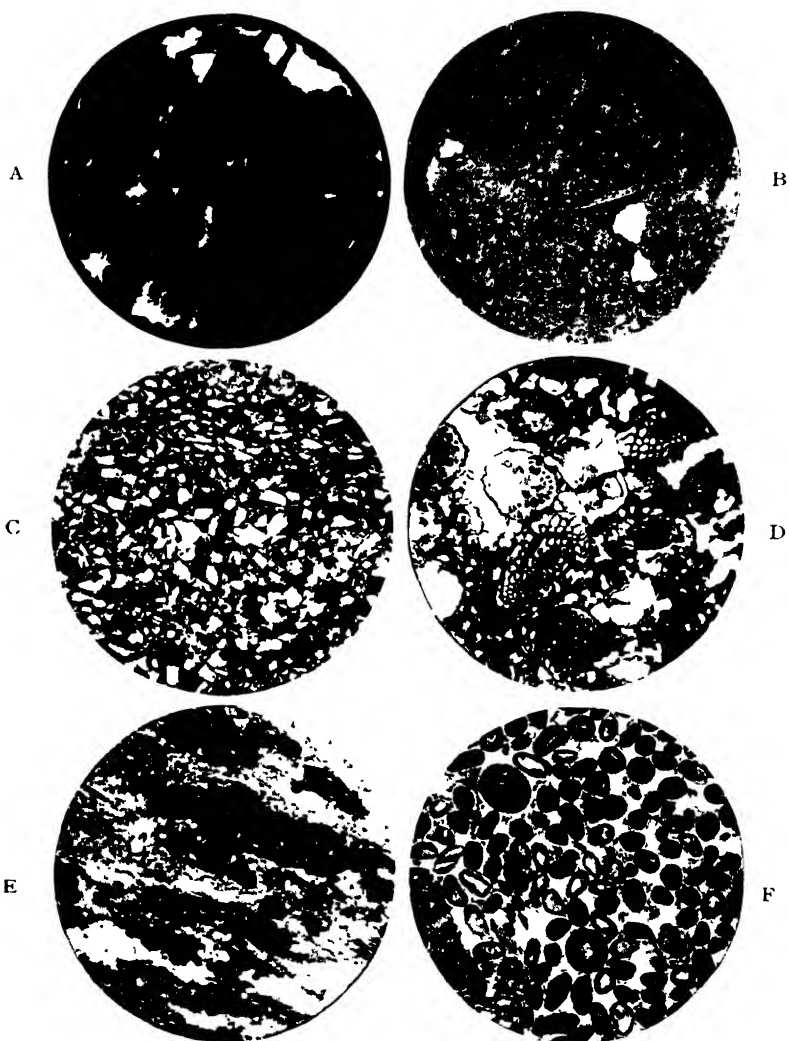


FIG. 90. Impregnated (Asphaltic) Limestone. Dept. of Gard, France
(half natural size).

often disrupting the normal relationship of the quartz particles. Sometimes a definite linear distribution of the bitumen is noted, in other examples, especially in fine-grained sandstones and siltstones, it more or less saturates the rock. Porosity plays an important part and where this is seen to vary, producing a "tight" sand, impregnation often stops abruptly. Impoverishment of the hydrocarbon causes it to appear in patches throughout the rock.



ASPHALT AND BITUMEN IMPREGNATED ROCKS.

- A. Asphalt, "Pitch Lake," Trinidad. [x 48.]
- B. do., Roumania. [x 15.]
- C. Impregnated Sandstone, Pechelbronn, Alsace [x 23]
- D. do *Fusulina* Limestone, Syzran, Simbirsk, Russia. [x 11.]
- E. Impregnated Limestone, Dept. of Gard, France. [x 15]
- F. do. Oolitic Limestone, Hanover. [x 25]

In limestones the manner of impregnation is largely determined by the nature of the organic components and the degree of crystallisation of the matrix. Often the fossil shells are sufficiently filled with mineral matter to avoid further contamination by the hydrocarbon, which is thus forced to confine itself to the matrix or to voids; on the other hand, where mineral infilling of shells or chambers is loose or wanting, or where cracks have been developed through which the original crude petroleum could penetrate, bitumen may be seen to fill not only the interiors, but often fractures and cracks in the shells and even in calcite crystals. Where fine-grained calcareo-argillaceous rocks are involved, e.g. marl, "patterning" of the bituminous material is very characteristic, due to the irregular porosity and permeability of the rock towards the hydrocarbon. In these cases it will often adhere to those planes or parts of the marl in which some degree of secondary crystallisation of the calcareous mud is apparent; where, however, it has been able to saturate the rock-particles, the whole specimen shows discoloration and high power magnification reveals thin films of asphalt coating the constituent particles. With excess of the hydrocarbon, seams of almost pure asphaltic bitumen tend to alternate with non-impregnated rock and a definitely banded structure is seen. The existence of jointing in such rocks determines "leakage" of the hydrocarbon from one layer to another and sometimes the spread of detrital grains which are thus locally transported: this phenomenon constitutes a very pretty study under the microscope.

Types. Asphalt from the Bermudez "Pitch Lake," Venezuela, with just over 3 per cent. mineral matter;¹ asphalt from the "Pitch Lake," Trinidad, B.W.I., with 27 per cent. mineral matter (crude material);² Glance Pitch or "Manjak" from Barbados;³ asphaltic impregnated sandstone, Pêchebron, Alsace;⁴ asphaltic limestone, Val de Travers, W. of Neuchâtel Lake, Switzerland, up to 10 per cent. normal impregnation;⁵ impregnated limestone, marl, sandstone and shale, St. Jean de Maruéjols, Department of Gard, France, between 5 and 16 per cent.⁶

Refs. ¹ H. Abraham, "Asphalts and Allied Substances." 4th ed. (Chapman and Hall, London), 1938, p. 146.

² *Ibid.*, p. 182; also A. W. Attwooll and D. C. Broome, "Trinidad Lake Asphalt." (The Baynard Press, London), 1935.

³ H. Abraham, *op. cit.*, p. 237; also R. J. Morgan, *Chem. Eng. Min. Rev.*, 13, 1921, p. 348.

⁴ P. de Chambrier, "Historique de Pêchebron." Paris, 1919.

⁵ M. Frey, "Die Asphaltilagerstätten im Schweizerischen Jura-Gebirge mit besonderer Berücksichtigung des Val de Travers." *Beit. Geol. Schweiz.*, 1922.

⁶ M. P. Nicou, *Ann. des Mines*, 10, 1906, p. 513.

General Refs.

G. H. Eldridge, *U.S. Geol. Surv.*, 22nd Ann. Rep., pt. i, 1901, p. 222.

A. Danby, "Natural Rock Asphalts." (Constable, London), 1913.

S. E. Ells, "Bituminous Sands, N. Alberta." *Canada Dept. Mines, Bull.* 632, 1926.

H. Abraham, *op. cit.*

(B5) PHOSPHATIC DEPOSITS. — These comprise the phosphatic rocks of organic origin as distinct from mineral apatite deposits and although sporadically developed on a

large scale in different parts of the world, they are comparatively unimportant as petrological studies. The group includes phosphorite, the primary metasomatic form of phosphate (hydro- or fluo-calcium carbonato-phosphate); guano, a friable or earthy type derived from the excrement of sea-birds etc.; the coprolites or fossil excreta of fishes, reptiles and mammals. Closely allied are the bone-breccias of similar composition. Many local varieties of these deposits are known. For present purposes it is unnecessary to split this group up into separate types and the following general description will suffice. (Pl. 42A, B, facing p. 421.)

Def. Phosphorite is the name applied to concretionary masses or other types of deposit of calcium phosphate of organic origin.

Lith. Primary, bedded phosphate deposits, e.g. phosphorite, vary considerably in external characters. The pure types are grey, brown or black, the last usually implying presence of hydrocarbon. Recognisable organic remains may or may not be in evidence; these vary from shell-fragments to bones and fish remains etc. Different structures prevail according to conditions of formation and to some extent with locality; for instance, in the Nigerian deposits W. Russ has described granular, nodular, fine and coarse vesicular and compact types.¹ In some granular examples small, rounded pellets of an amorphous form, collophane (p. 269) may occur, giving the rock a pseudo-oolitic character. The nodular type "has a conglomeratic appearance derived from the ellipsoids and irregular cylindrical nodules of calcium phosphate."² The vesicular varieties are altered products into which enter phosphates of iron and alumina. Guano, coprolites and the "bone-phosphate" of the breccias are for the most part amorphous; guano is dry, pulverulent, earthy and friable (under arid conditions) and contains considerable impurity in the form of nitrate, lime carbonate etc. Coprolites are grey, green or brownish-black in colour; in some cases they are phosphatised matter entirely, in other examples fossil-shell fragments are included. Various phosphatic nodules found in different strata may either be coprolites in the strict sense, or be composed of collophane, calcium carbonate and mineral matter.

Text. Phosphorite: fine, compact, homogeneous, to coarse, earthy vesicular (like pumice); guano is earthy, friable; nodules and coprolites are usually smooth, sometimes "soapy"; bone-phosphate is rough, powdery, or hard and compact, sometimes coated with secondary crystalline material.

Min. Comp. These phosphates are essentially varieties of calcium phosphate, with or without fluorine, calcium carbonate, iron phosphate, aluminium phosphate etc. Among specific minerals may be mentioned collophane, dahllite and francolite. Associated impurities include quartz, calcite, dolomite, chert, pyrite, marcasite, glauconite etc.

Micro. These rocks are among the most variable materials to study microscopically; practically no two examples are alike. Except the

¹ *Geol. Surv. Nigeria, Bull.* 7, 1924, p. 11.

² *Op. cit.*, p. 12.

rarer compact varieties of phosphate rock, most examples have the appearance of "conglomerates" in which the "pebbles" are rounded and of varying sizes, set in a matrix which is clear, turbid or iron-stained. For the most part, the larger constituents are phosphate grains, the matrix is a mixture of phosphate, aluminium phosphate, carbonaceous matter and detrital minerals. Fossil-shell and bone-fragments are common. Some of the phosphate is crystalline and gives definite optical reactions; for instance, in some types of granular, amorphous phosphate there is interstitial aluminous phosphate with bluish-grey aggregate birefringence. Much of this granular, amorphous material is probably collophane. Phosphatic nodules, coprolites etc., are amorphous, but frequently some sort of nucleus is observed in thin section, e.g. shell-fragment, bone, rarely inorganic matter. Phosphate casts of *foraminifera* and structural grains replacing those organisms are often observed. Various stages in phosphatic replacement of limestones occur. In bone-breccias in which phosphate prevails, both bone-fragments and matrix may be of lime phosphate, but usually some degree of secondary alteration is noted, with the production of iron phosphate, calcite and silica.

Types. Upper Cretaceous (Cambridge Greensand), Cambridgeshire, phosphatised fossils, phosphate nodules etc.;¹ Lower Chalk, Cambridgeshire, etc., calcareo-phosphatic nodules of green colour, brown-yellow inside;² phosphate rock, Abeokuta Province, Nigeria, with iron and aluminium phosphates etc.;³ guano deposits of Peru, Christmas Island (Indian Ocean), Navassa Island (Caribbean) etc.;⁴ Suffolk Box-stones.⁵

Refs. ¹ F. R. C. Reed, "Geology of Cambridgeshire." (University Press, Cambridge), 1897, p. 100.

² *Ibid.*, p. 127.

³ W. Russ, *op. cit.* (N.B.—This work contains some excellent photomicrographs of phosphate rocks.)

⁴ W. H. Twenhofel, "Treatise on Sedimentation." 1926, p. 400.

⁵ P. G. H. Boswell, *Geol. Mag.*, 1915, p. 253.

General Refs.

A. Carnot, *Ann. des Mines*, 10, 1896, p. 137.

O. Stutzer, *Zeit. f. Prakt. Geol.*, 19, 1911, p. 73.

L. Cayeux, "Roches sedimentaires." (Imprimerie Nationale, Paris), 1916, p. 235.

A. L. du Toit, *Geol. Surv. S. Africa*, 10, 1917.

J. W. Gregory, *Trans. Geol. Soc. Glasgow*, 16, 1917, p. 115.

L. Owen, "Phosphate Deposits of Ocean Island." *Quart. Journ. Geol. Soc.*, 79, 1923, p. 1.

F. W. Clarke, "Data of Geochemistry." *U.S. Geol. Surv., Bull.* 770, 1924, p. 523.

A. F. Hallimond, *Mem. Geol. Surv., Spec. Rep. Min. Resources, Gt. Brit.*, 29, 1925, p. 35.

J. H. C. Martens, "Sand, etc., Florida." *Florida State Geol. Surv., 19th Ann. Rep.*, 1928, p. 33 (p. 43 for collophane).

(C) Chemical Origin

This group comprises all inorganic deposits dependent for their formation on precipitation from solution, or on some

definite chemical replacement of a pre-existing mineral by another mineral of different composition, the latter process usually referred to as "metasomatic" change or "metasomatism." On account of the obvious influence of organic agency in many geochemical reactions and the constant overlap between organically- and chemically-formed rocks in many instances, the present group is admittedly to that extent artificial. The example already discussed (p. 405) is that of the ferruginous deposits, deliberately relegated to this chemical group notwithstanding the admitted influence of bacterial organisms in their formation.

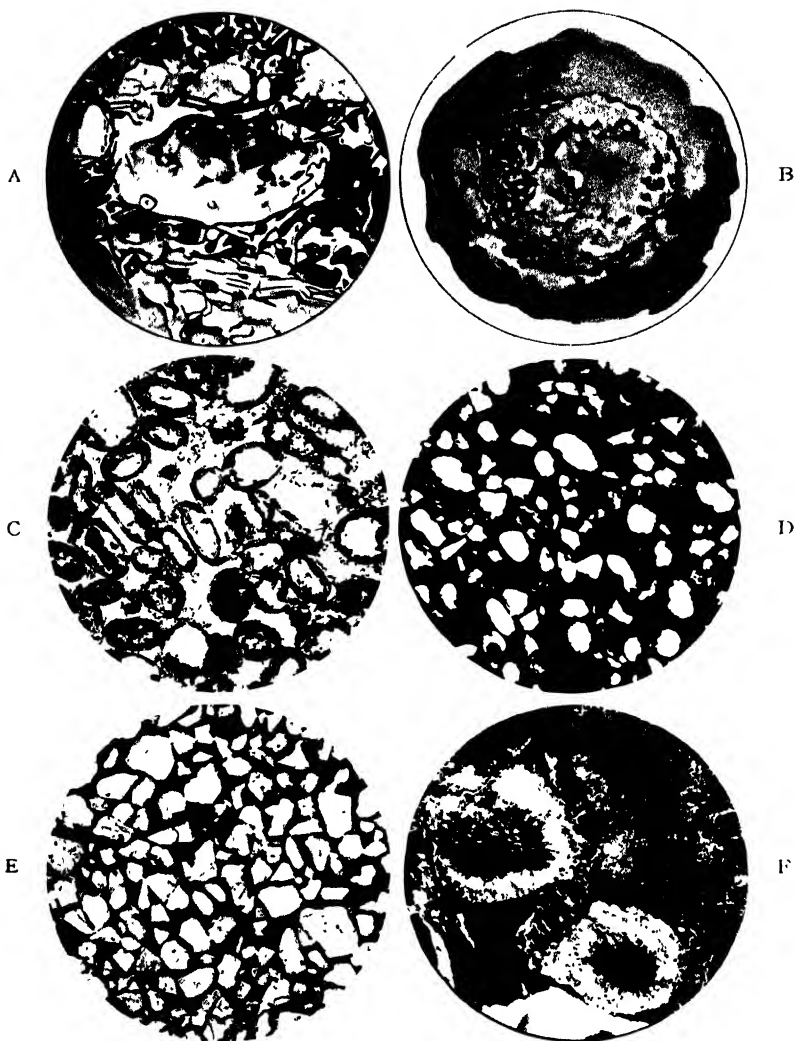
On the other hand, a majority of rocks falling naturally into this category is clearly inorganic, *e.g.* travertine, calc-sinter, gypsum, anhydrite, rock-salt etc.; this is a sufficient justification for retaining a division which shall include deposits of such definite chemical origin and which further lends itself to internal rearrangement of types on the logical basis of chemical composition.

The real distinction between organic and chemical deposits lies in direct or indirect contribution: the former are primarily concerned with accumulation of actual organic substance; the latter may and often do imply organic agency or influence in their achievement, but the actual organisms concerned (or their remains) may not be manifest; in fact it is rarely so in these rocks.

The study of chemically-formed deposits is valuable from many points of view; their petrology (possibly "mineralogy" would be the more accurate term in most cases) is distinctive and interesting; their stratigraphical occurrences are always an inspiration of problems of genesis and relationship to their associated rocks; their significance in illustrating the principles of cementation of incoherent sediment—the authigenic factor—cannot be overlooked; while to petroleum geologists in particular, such materials as rock-salt, gypsum and anhydrite are of vital importance in many oilfields.

For these and other reasons, chemically-formed deposits invite careful study and the same diligent use of the microscope as is accorded to more complex rock-types.

Following the scheme of sub-classification adopted hitherto, the four main divisions are:—



PHOSPHATES AND BEDDED IRON-ORES.

- A. Calcium Phosphate Nodule, Oshosun, Nigeria [x 50.]
 B. Phosphate Rock, Oshosun, Nigeria. [x 5.]
 C. Cleveland Ironstone (Liassic), Yorks. [x 23.]
 D. Ironstone (Estuarine), Thrapston, Northants. [x 25.]
 E. Abbotsbury Iron-Ore (Corallian), Abbotsbury, Dorset. [x 15.]
 F. Pyritic Blackband (Coal Measures), Powell Duffryn, N. Wales [x 14.]

- (C1) CALCAREOUS (p. 421).
- (C2) FERRUGINOUS (p. 423).
- (C3) SILICEOUS (p. 425).
- (C4) SALINE (p. 426).

(C1) **CALCAREOUS DEPOSITS OF CHEMICAL ORIGIN.**—This division, relieved of those carbonate developments in which organic influence has clearly operated (dolomitic limestone, oolitic and pisolitic structures, group B), though chemical action in each case has undoubtedly taken place, may be said to be sufficiently distinctive. It includes such deposits as travertine or calc-sinter, stalactite and stalagmite growths, dolomite (in part). In connexion with the latter, much difference of opinion exists as to whether this substance can originate *per se* as a direct result of chemical precipitation from solution, many writers claiming the essential action of magnesia-secreting organisms as instrumental to its formation. The author agrees with those who maintain that the mineral can be generated independently from solution. For instance, dolomite occurs in association with rock-salt, gypsum, anhydrite etc., in the Trias of Germany, in which development it does not in the least suggest replacement of an original limestone.

These deposits may be subdivided as follows:—

- (C1.1) Calcium Carbonate: Calcite (p. 421).
- (C1.2) Dolomite (in part) (p. 422).

(C1.1) **CALCIUM CARBONATE: CALCITE.** (See also B1, 1, p. 392.)

Lith. This subdivision includes the following variable examples:—travertine, calc-sinter, calc-tufa, stalactite and stalagmite growths; the first three are practically identical, consisting of accumulations of calcium carbonate possessing cellular, concretionary, compact, or earthy and porous tendencies. Stalactites are the pendent growths of calcium carbonate from the roofs of caves etc.; stalagmites the corresponding accumulations on the floors of such recesses. "Onyx Marble," a misnomer, is a well-banded variety of stalagmitic carbonate and belongs here. In the case of travertine etc., deposition is often quite irregular, producing encrustations and earthy accumulations rather than well organised structures, the characteristic of stalactites and stalagmites, where some development of concentric growth is always apparent when the specimen is split transversely. Colour varies from white, yellow to brown.

Text. Compact to earthy, friable.

Min. Comp. Essentially calcium carbonate, but often with impurities such as iron carbonate, limonite, silica, hydrocarbon etc.

Micro. The crystalline nature of these rocks is seldom in doubt when tested under the microscope with polarised light. All the characteristic properties of calcite (p. 257) are observed, while the presence of impurities is easily detected. The concentric growth-layers of the stalactites etc., are often picked out with impurity, e.g. limonite, while subsidiary radial structures may be observed. In the tufas, some proportion of the mineral is powdery and appears to be amorphous; usually no special structure is apparent unless encrustation about some particular nucleus has taken place uniformly.

Types. Carboniferous Limestone of Derbyshire etc., for all these types of carbonate.

General Refs.

V. C. Allison, *Journ. Geol.*, 31, 1923, p. 105.

W. H. Twenhofel, "Treatise on Sedimentation." (Ballière, Tindall and Cox, London), 1932, p. 324.

(C1. 2) **DOLOMITE** (in part). (See also B1. 2, p. 395.)

Lith. Dolomite occurring as the mineral (not as a partial replacement of limestone) and in intimate association with other inorganic deposits, is an interesting development. In its massive form it constitutes dolomite rock, a white, grey, green, brown, sometimes pinkish, crudely stratified deposit, often with a somewhat pearly lustre. Brown staining is mainly due to ferrous carbonate, other prominent colouring may be due to manganese compounds. Usually dolomite is close-grained, uniform and difficult to distinguish from limestone except by acid test; on the other hand, in veins or cavities (the latter very common in some examples), characteristic curvilinear crystals, resulting in "saddle-shaped" aggregates, may be observed, when the mineral is at once easily recognised.

Text. Medium, compact, sometimes friable.

Min. Comp. Essentially carbonate of calcium and magnesium, but with impurities of iron, sometimes manganese; often intimately associated with gypsum, barite, silica, more rarely celestite.

Micro. Under the microscope the simple rhombs of dolomite are, if developed, very characteristic; alternatively, somewhat rectangular forms as constituents of aggregates may be displayed. Where individual crystallisation is obliterated by interferent mass-precipitation, a mosaic of irregular grains, almost indistinguishable from calcite, results; in such cases only a chemical test yields positive diagnosis (p. 258). In field-association with gypsum, anhydrite, rock-salt etc., these minerals may be looked for in the slide and are usually apparent to a greater or lesser extent, especially in joint-channels or cavities. A complete absence of organisms or organic structures is one of the differentiating features between dolomite and dolomitic limestone, though where the latter forms part of the series, separation of the two types is often an exceedingly difficult matter.

Types. Trias, Keuper Marls, Charnwood, Leicestershire. "quartzose dolomite," compact, granular, blue-grey crystalline rock composed of perfect rhombs of dolomite associated with quartz, aluminous silicate and barite;¹ other occurrences from the same formation show perfect rhombs of dolomite;² Raibl Beds, Tyrol, dolomite associated with gypsum.³

Refs. ¹ T. O. Bosworth, "Keuper Marls around Charnwood." *Leicester Lit. and Phil. Soc.*, p. 54, 82, 84, 108.

² C. G. Cullis, *Rept. Brit. Assoc., Adv. Sci.*, Leicester, 1907, p. 506.

³ M. M. Ogilvie, *Quart. Journ. Geol. Soc.*, 49, 1893, p. 1.

General Refs.

F. M. Van Tuyl, *Iowa Geol. Surv.*, 25, 1914, p. 262.

Mem. Geol. Surv., Spec. Rep. Min. Resources, Gt. Brit., 6, 1918, p. 190.

F. W. Clarke, "Data of Geochemistry." *U.S. Geol. Surv., Bull.* 770, 1924, p. 565.

(C2) FERRUGINOUS DEPOSITS. — (See also Group B3, p. 405).—Prevalent ideas with regard to the nature and origin of ferruginous deposits have been considerably clarified by A. F. Hallimond, who has investigated the bedded iron-ores of England and Wales, to which reference has already been made elsewhere.¹ Apart from the action of *bacteria* or *algæ* in instigating or influencing certain chemical reactions from which these rocks result, the essentially inorganic character of these deposits is now generally admitted, even to the extent of denying the probability of oolitic ironstones having been derived by metasomatic process from oolitic limestones. For present purposes it will suffice to recognise two contrasted occurrences.

(C2. 1) Bedded Iron-Ores (p. 423).

(C2. 2) Bog Iron-Ore (p. 425).

(C2. 1) **BEDDED IRON-ORES.**

[Pl. 42 C-F, facing p. 421.]

Lith. A. F. Hallimond divides the bedded iron-ores into two principal groups, the ferrous and the ferric ores; the former are the chamosite and chamosite-siderite mudstones, non-chamositic siderite mudstones, and siderite limestones; the latter include the ferric chamosite oolites, the limonite oolites, primary hematites and glauconite rocks. The mudstones correspond to the older terms "clay ironstone" or "black-band ironstone" of the text books. Megascopically the chamosite and chamosite-siderite mudstones vary greatly; the colour is green or brown; oolitic developments and compact mudstone alternating; organic remains and markings common. The siderite mudstones are on the whole darker in colour, of finer texture, nodular, or in thin beds; they resemble "cement-stones." Closely allied to them are the sphærosiderite rocks, in which spherulitic grains of the mineral are embedded in clay (p. 336). The sideritic limestones differ from the preceding types in consisting of aggregates of shell-fragments cemented with calcite and siderite. Of the ferric ores, the ferric chamosite oolites vary from black to red and brown oolitic and pisolitic mudstones, often highly magnetic, with conspicuous bedding and limonite cement; occasionally pyrite in nests. The limonite oolites are composed mainly of oolites of that mineral, not of chamosite as in previous types; they may be closely or sparsely packed, in the latter case the matrix of sandstone or mudstone is usually fine and homogeneous except where organic fragments are common; colour, grey, brown, reddish-brown. The primary hematites include turgite or hematite

¹ *Mem. Geol. Surv., Spec. Rep. Min. Resources, Gt. Brit.*, 29, 1925.

occurring as pebbly or nodular beds, or in brick-red massive varieties etc. The glauconitic rocks include ironstones in which, as a result of weathering of sands containing that mineral in abundance, iron is concentrated mainly as limonite, though in some cases with a considerable amount of siderite; there is often a clay matrix, while the development of limonitic "boxstones" is characteristic; this material is in the nature of an "iron pan."

Text. Variable, from fine to medium grain in the mudstone facies, coarse to earthy in the oolitic developments.

Shape. Detrital particles SA.

Min. Comp. Al. Quartz, iron-ores and miscellaneous accessory minerals.

Au. (including chemical precipitates), chamosite, siderite, dolomite, ferric oxide, magnetite, pyrite, glauconite, clay-substance, calcite, limonite, phosphates (collophane) etc.

Mech. Comp. In the siderite mudstones, oololiths 1/60 in. in diameter; in average cases siderite crystals are about 0.02 mm. in diameter; detrital grains mainly of the silt grade.

Micro. In these rocks the oololiths are usually of chamosite, one of the chlorite group of minerals and they may or may not contain siderite in rhombs or irregular grains. Siderite oololiths are much less common; these are set in a fine chamosite-mud ground-mass, often rich in siderite in rhombs or crystal-bunches. The chamosite ground-mass is green to brown in colour. Quartz, dolomite and accessory minerals are scattered throughout the rock. In the mudstones the ground-mass may consist of quartz, felspar, mica and clay-substance, with or without chamosite. A characteristic feature of many of the mudstones is the abundance of fossil-shell fragments often replaced by rhombs of siderite; other organic remains include fish-teeth, casts of boring worms, plant debris etc. When sphærosiderite occurs, the spherulites are scattered in a clay-matrix; the former "are built up of long narrow fibrous crystals with straight extinction, radiating from the centre and often terminating in an irregular angular outline; sometimes the component crystals are fewer and broader. The ground-mass is generally of fireclay type, and is sometimes present in so small an amount that the spherules meet, forming polygonal cells. When quartz etc., is present in the ground-mass, some of the coarser grains are often included in the spherules, an indication that these grew within the clay."¹ The sideritic limestones exhibit siderisation in all stages from cementing medium to complete replacement of calcite (metasomatism). In the limonite oololiths, the matrix consists of weakly birefringent clay-substance (? altered chamosite) with siderite, dolomite, quartz etc.; the oololiths themselves are brown, translucent, and with radial-fibrous and concentric structure. Sometimes each grain is coated with an isotropic film of chamosite. In the glauconitic varieties, this mineral occurs conspicuously; the oololiths are of limonite showing concentric structure, set in a brown sideritic cement which also shows alteration to limonite.

Types. Middle Lias, Cleveland Ironstone, Yorkshire, example of chamosite mudstone and chamosite-siderite mudstone; also oolitic Cleveland Ironstone; Wealden, siderite mudstone, also sphærosiderite (Fairlight Clay, Sussex); Lower Cretaceous, Claxby Ironstone, Lincolnshire, example of limonite oolite; Lower Greensand, Seend, Wiltshire, glauconitic ironstone with limonite boxes etc.; Abbotsbury Iron-ore,

*Ref.*¹ A. F. Hallimond, *Mem. Geol. Surv., Spec. Rep. Min. Res., Gt. Brit.*, 29, 1925, p. 67.

Dorset, and Westbury Ironstone (Corallian), Wiltshire, both examples of limonite oolites.¹

(C2. 1) **BOG IRON-ORE.***

Def. Bog iron-ore denotes an impure ferruginous deposit formed in swampy ground by oxidising action of atmospheric or bacterial agency.

Lith. In brittle flakes, thin beds, aggregates or as filmy matter on water-surface; material usually soft, porous and of brown colour. Clay is usually associated with the solid bog-ore, in fact often underlies it; plant remains are common.

Text. Fine, smooth, to earthy and friable.

Min. Comp. Limonite, siderite, clay-substance, with (locally) iron silicate, iron sulphate, vivianite, "wad" or bog manganese, humus etc.

Micro. In thin section, the solid iron-ore exhibits a brown to red colour, usually of fairly homogeneous material, much of which is optically inert, though easily studied by means of reflected light. Siderite when present is detected by its characteristic twinkling with the polariser. Vivianite is of comparatively rare occurrence and is suggested by bluish-green or dark blue prismatic crystals. Organic structures are very conspicuous, normally consisting of rootlets, twigs, leaves, sometimes seeds, frequently replaced by limonite.

Types. Various lacustrine and fluviatile iron-ores and "iron pans"; Scotland, Sweden etc.

General Refs.

N. S. Shaler, 10th *Ann. Rep.*, U.S. Geol. Surv., pt. i, 1890, p. 305.

E. C. Harder, U.S. Geol. Surv., *Prof. Paper* 113, 1919.

R. Beck, quoted by W. H. Twenhofel, "Treatise on Sedimentation," (Ballière, Tindall and Cox, London). 1932, p. 819; also other references therein cited.

(C3) **SILICEOUS DEPOSITS.**—Included under this heading are those rocks owing their existence primarily to inorganic agency, *viz.* precipitation from solution in which silica in one form or another is prevalent. Here belong siliceous sinter and to a large extent chert and flint. These latter, however, are concerned with recognisable organic remains contributory to their formation, more especially in the case of chert and in the present state of our knowledge it seems desirable to discuss them under the heading of organically-formed rocks, though admittedly the claim of the chemical group is strong. This is another case of difficulty of classification raised by a genesis which contemplates more than one mode of origin. Accordingly chert and flint are described as types of group (B) (p. 390), leaving siliceous sinter as the example of the purely chemical siliceous deposit; even in this case it should be noted

¹ A. F. Hallimond, *op. cit.* (N.B.—This work so far supersedes pre-existing accounts of these particular rocks as to render further references superfluous, though many will be found therein as footnotes where appropriate.)

* See also under *Limonite*, p. 309.

that organic agency has on more than one occasion been invoked to account for its formation.

(C.3. 1) **SILICEOUS SINTER.**

Def. Siliceous sinter ("geyserite") is a solution deposit of silica from thermal springs.

Lith. This material is chiefly deposited as earthy encrustations in the vicinity of hot springs or geysers, hence the synonymous term "geyserite." It varies in colour from yellow to pink, green, brown, variation being noted with temperature at the time of formation. These colours have been attributed to gelatinous precipitation influenced by certain *algæ*, but the mechanism is not perfectly understood. Many examples resemble accumulated concretions, sometimes with a kind of "onion" structure, at other times having the appearance of "cauliflower" structure.

Text. Usually earthy, porous and friable.

Min. Comp. Amorphous silica, opal, with impurities of iron, manganese etc.

Micro. Siliceous sinter examined under the microscope exhibits characteristic "growth" structure in ordinary transmitted light, but remains for the most part isotropic with polarised light. Few structures which can be termed even micro-organic are observed; certainly *algæ* are not conspicuous in the cold, consolidated rock. Colouring matter is finely disseminated and is not attributable to any particular crystalline substance. Fibrous sinter is not uncommon, but individual fibres do not yield optical reactions.

Types. Yellowstone Park, U.S.A.; hot springs of Taupo, New Zealand; geysers of Iceland etc.

General Refs.

W. H. Weed, *U.S. Geol. Surv., 9th Ann. Rep.*, 1889, p. 613; also *Am. Journ. Sci.*, 37, 1889, p. 351.

G. W. Tyrrell, "Principles of Petrology." (Methuen, London), 1926, p. 223.

R. B. Sosman, "The Properties of Silica." (Chemical Catalogue Company, New York), 1927, p. 796.

W. A. Tarr, "Terminology of the Chemical Siliceous Sediments." *Committee on Sedimentation, Nat. Research Council, U.S.A.*, 1936.

(C4) **SALINE DEPOSITS.** — This group covers a variety of chemically-formed rocks characteristic of certain well-defined environments, *e.g.*, lagoons, inland lakes, relic (land-locked) seas etc. It includes chlorides, sulphates, borates, nitrates etc., occurring as products of precipitation usually in regular beds or layers, but lacking "stratification" in the accepted sense. Apart from such developments *per se*, certain of the compounds considered here also occur as replacements of pre-existing rocks, more particularly those of the calcareous group; the sulphates are implied in this connexion. Contrary to usual belief, microscopical examination of these sedimentary salts

shows that they are among the most variable rocks found in nature, especially as regards structure; this may be of such a distinctive type as to characterise a particular development over a large area and through a limited thickness of deposit; thus careful study of structural features, particularly in regard to gypsum and anhydrite occurrences, is a matter of considerable moment in the identification of horizons in thick saline sequences. Such study is, however, much facilitated when chemical analyses of the rocks in question are available; these serve as a guide to the anticipation of closely allied products whose mineralogical characteristics may not be sufficiently obvious to aid their differentiation from the chief constituents. The types chosen to illustrate this group are:—

- (C4. 1) Chlorides (p. 427).
- (C4. 2) Sulphates (p. 428).
- (C4. 3) Nitrates and Borates (p. 430).

(C4. 1) **CHLORIDES.**

[Pl. 43 A, facing p. 428.]

Lith. The chief examples of this group are rock-salt (halite) and sylvite (potassium chloride); the latter is comparatively rare. Rock-salt occurs either in recognisable crystal-form (halite) with marked cubic cleavage, in granular masses, or as thick, structureless, massive beds. In colour it varies from colourless to white, yellow, red, purple (with increasing impurity). Possesses a strong saline taste and readily dissolves in water. Many specimens exhibit considerable distortion. Sylvite is also an isometric mineral with strong cleavage, though seldom so conspicuous as in the case of rock-salt. It occurs as granular or massive developments, nearly always accompanied by impurities.

Text. Fine, glassy or "sugary."

Min. Comp. Halite (NaCl), with many impurities and associated salts, e.g. sulphates, carbonates, clay-substance, silica etc. Sylvite (KCl), usually with halite, silicates, nitrates etc.

Micro. Both rock-salt and sylvite are normally isotropic in polarised light, though some examples exhibit anomalous birefringence, probably due to impurities in most cases; strain-phenomena are possible. In ordinary transmitted white light the refractive index of rock-salt is less than Canada balsam, but by a small amount, so that the outlines of the crystals or sections of massive material are not prominent; with sylvite the R.I. is considerably less than that of balsam, with the result that a shagreened surface with bold outlines is characteristic. Colouring matter in both salts is noted as fine disseminations, seldom suggestive of recognisable minerals, except limonite. The cleavage is often well displayed where crystals are in evidence.

Types. Triassic salt deposits, Northwich, Cheshire; Preesall, Lancashire; Staffordshire etc.;¹ rock-salt and sylvite, Stassfurt, Germany.²

Refs. ¹ *Mem. Geol. Surv., Spec. Rep. Min. Res., Gt. Brit.*, 18, *Rock-salt and Brine*, 1921.

² F. W. Clarke, "Data of Geochemistry," *U.S. Geol. Surv., Bull.* 770, 1924, p. 222.

General Ref.

A. W. Grabau, "Principles of Salt Deposition." (McGraw-Hill Book Company, New York), 1920.

(C4. a) SULPHATES.

[Pl. 44 A-E, facing p. 430.]

Lith. This group includes gypsum, anhydrite, barite and celestite as the commonest representatives of accumulated "salt" deposits. As individual minerals they have already received consideration in Ch. IX, to which further reference for mineralogical detail should be made. The following notes refer to their occurrence *en masse*. Gypsum normally occurs in massive aggregates of mutually interferent crystals, often decidedly fibrous and with a saccharoidal structure. In colour it is white to pale pink, red or brown, the colouring matter being due to impurity, often to iron compounds or finely divided rock-flour.

Anhydrite also occurs massive, sometimes with distinct fibrous development; crystallisation may be very coarse, due to the packing together of crudely rectangular prismatic crystals. The structure is of a schistose character in some examples. Colour white, grey, blue or red. It is much harder than gypsum, this property affording a quick test between the two minerals in hand-specimen.

Barite in sediments is frequently in the form of isolated crystalline masses; it seldom achieves the bedded character of the other sulphates, being essentially a vein-mineral, though exceptionally it may result from the weathering of a barite-bearing limestone, thus assuming the character of a residual deposit. Its usual occurrence is in massive, platy, crystalline aggregates, often with prominent and beautifully formed crystals of characteristic habit (p. 248). Earthy and fibrous varieties occur. Colour varies from white to yellow, brown or red according to degree of purity. This mineral is much heavier than the other sulphates here considered and this constitutes a discriminating test in large specimens; it does not effervesce with acid, which distinguishes it from calcite.

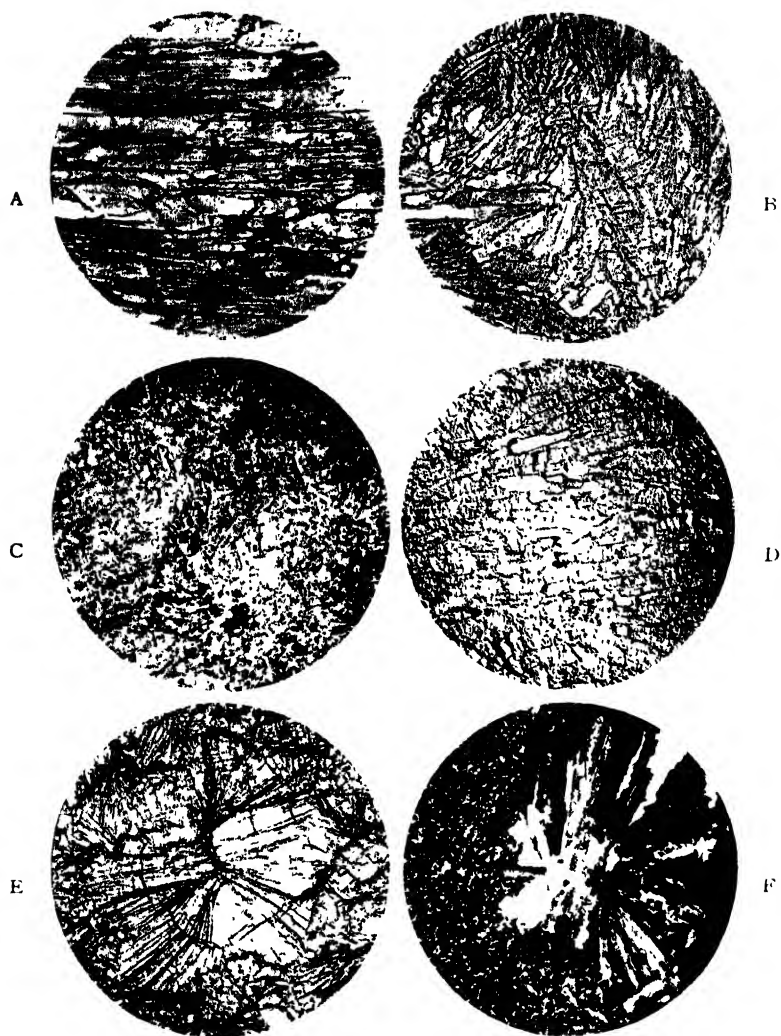
Celestite generally appears in granular masses or as an aggregate of coarse crystals. Some degree of cleavage is usually apparent. Colour white or cream.

These sulphates seldom occur free of impurity in the rock-form; every gradation is met with between the slightly contaminated mineral substance to those developments in which sands, marls, clays, shales, limestones etc., are intimately associated; various stages of replacement of limestone by the sulphates are possible and are observed.

In some cases it will be found that neither megascopic nor microscopic examination will result in positive identification of each mineral without recourse to physical and chemical tests. The variations of these deposits are very great and the possibility of more than one species being closely associated with another in the same sample, renders it always desirable to conduct such confirmatory tests. At the same time much more can be done with thin sections under the microscope than is generally realised with these materials.

Text. Gypsum: saccharoidal; smooth; rough; friable; earthy; fibrous. Anhydrite: schistose; fibrous; scaly. Barite: fine; crystalline; granular, sometimes laminated. Celestite: granular; coarse; cavernous; smooth, crystalline.

Min. Comp. Gypsum: impurities commonly iron-ore, silica, calcite, clay. Anhydrite: impurities are gypsum, rock-salt, calcite, iron-ores etc.



CHLORIDE AND SULPHATE

- A. Rock-Salt (Triassic), Cheshire. [x 15.]
- B. Anhydrite, Cropwell Bishop, Notts. [Bladed Type, x 15.]
- C. do Cote Hill, Cumberland. [Granular Type, x 23.]
- D. do Cropwell Bishop, Notts. [Foliated Type, x 15.]
- E. do Segeberg, Germany. [Spherulitic (radial) Type x 15.]
- F. Anhydrite-Gypsum Rock (Permian), Hatfield, nr Doncaster, Yorks.
[Crossed Nicols, x 25.]

Barite: impurities commonly silica, metallic ores, hematite, marl, sandstone etc. Celestite: other sulphates, baryto-celestite, baryto-calcite, limestone, metallic ores etc.

Micro. Gypsum often presents a "porphyritic" structure in thin section under the microscope, when large, prismatic crystals are embedded in a fine crystalline gypsum ground-mass; the large crystals may or may not exhibit tendencies to parallel orientation, usually not. Other modes of occurrence recall the "ophitic" structure of igneous rocks; in this case large platy gypsum crystals enclose well-formed euhedra. Mutually interferent crystalline types present a granulitic structure. Bunches of fine gypsum needles may form in irregular fashion or as spherulites or partial spherulites, the latter displaying a radial structure. If anhydrite is present, it usually stands out clearly by virtue of its higher refractive index (gypsum is lower than Canada balsam) and strongly developed cleavages. Specks of iron-ore, veins of other minerals, patches of distinctive colouring matter, are all common features of this rock-type.

Anhydrite is usually much more coarsely crystallised than gypsum, often in very marked rectangular, prismatic crystals packed together, often orientated in one direction within the boundaries of distinct aggregates. A pseudo-cubic cleavage is normally conspicuous. Other modes of occurrence are spherulitic, radial, irregular clusters, granular (when the rock is made up of scattered stumpy rectangular grains set in an extremely uniform matrix), aggregates of rounded (? corroded) grains and "feathery" forms. In many examples every stage in the conversion of anhydrite to gypsum may be detected; alternating layers of anhydrite and gypsum are characteristic in some developments, yielding a laminar structure. The passage of limestone into anhydrite may be observed in appropriate examples, especially in dolomitic rocks.

Barite varies considerably from coarsely crystalline types (somewhat rare) to aggregates of mutually interferent crystals of prismatic or granular habit; sometimes the mineral is extremely compact and almost cryptocrystalline. A tendency to develop curved laminae is not uncommon. Impurities are on the whole commoner than with gypsum and anhydrite and are frequently identifiable as definite minerals or rock-particles. The earthy type is hard to distinguish from other sulphates by microscopical means alone; as, in fact, are often the crystalline developments; sometimes the alternating glassy and dull white, opaque lustre by reflected light—exhibited by certain forms of the mineral—is sufficiently diagnostic. It has a much higher refractive index than either gypsum or anhydrite. Although possessing similar cleavages to the latter, it seldom displays the markedly "cubic" structures of that mineral.

Celestite is so very close in its properties to anhydrite that microscopical distinction is seldom possible; confirmatory tests should always be sought if this mineral is suspected. A bluish tinge to the platy crystals or to the fibrous forms (if developed) is very characteristic; the occurrence of scattered aggregates of fine, fibrous crystals in an otherwise homogeneous granular ground-mass, is suggestive of celestite, while in most examples the interference colours are of a lower order than anhydrite or barite.

Types. **Gypsum:** Permian, Kirkby Thore, Westmorland;¹ from the Upper Marls (Permian) of Nottinghamshire and Yorkshire; from the Saliferous Marls (Permian) of Durham; from the Keuper Marls (Trias) of Nottinghamshire,² Derbyshire, Leicestershire etc.; from the Purbeck (Sub-Wealden Boring), near Battle, Sussex (free of anhydrite).³
Anhydrite: localities as above, except Sussex.⁴

Barite: chiefly as vein-stone from Palæozoic formations in Northumberland, Durham, Westmorland, Shropshire and Welsh Borders; residual material (Carboniferous Limestone) Bradwell Moor, Derbyshire; concretionary crystalline masses in Fuller's earth, Nutfield, Surrey.⁵

Celestite: Trias, Keuper Marl, Yate district, Gloucestershire, in sporadic masses and lenticles.⁶

Ref.¹ *Mem. Geol. Surv., Spec. Rep. Min. Res., Gt. Brit.*, 3, 1915.

² W. A. Richardson, *Mineral. Mag.*, 19, 1920, p. 77, and 1921, p. 196.

^{3, 4, 6} *Mem. Geol. Surv., op cit.*

⁵ *Mem. Geol. Surv., Spec. Rep. Min. Res., Gt. Brit.*, 2, 1922.

General Ref.

A. W. Grabau, "Principles of Salt Deposition" (McGraw-Hill Book Company, New York), 1920.

C4. 1) NITRATES AND BORATES. [Pl. 44 F, facing p. 430.]

Nitrates are exemplified by the sodium nitrate or "caliche" deposits of Chili and Peru, the borates by borax (or the crystallised mineral "tincal") of volcanic origin in Tuscany etc. From a petrological standpoint, these are comparatively unimportant rocks. The commonest example, soda nitre (Nitratine), is a white, grey or yellow, soft, rather earthy material; it is crystalline, like calcite, and "twinkles" with plane polarised light. There are many varieties of nitrate compounded with calcium, magnesium salts etc., for which reference must be made to appropriate literature (see below). Borax crystallises in the monoclinic system and occurs as fine, slender crystals embedded in mud. "Tincal" is the crude mineral.

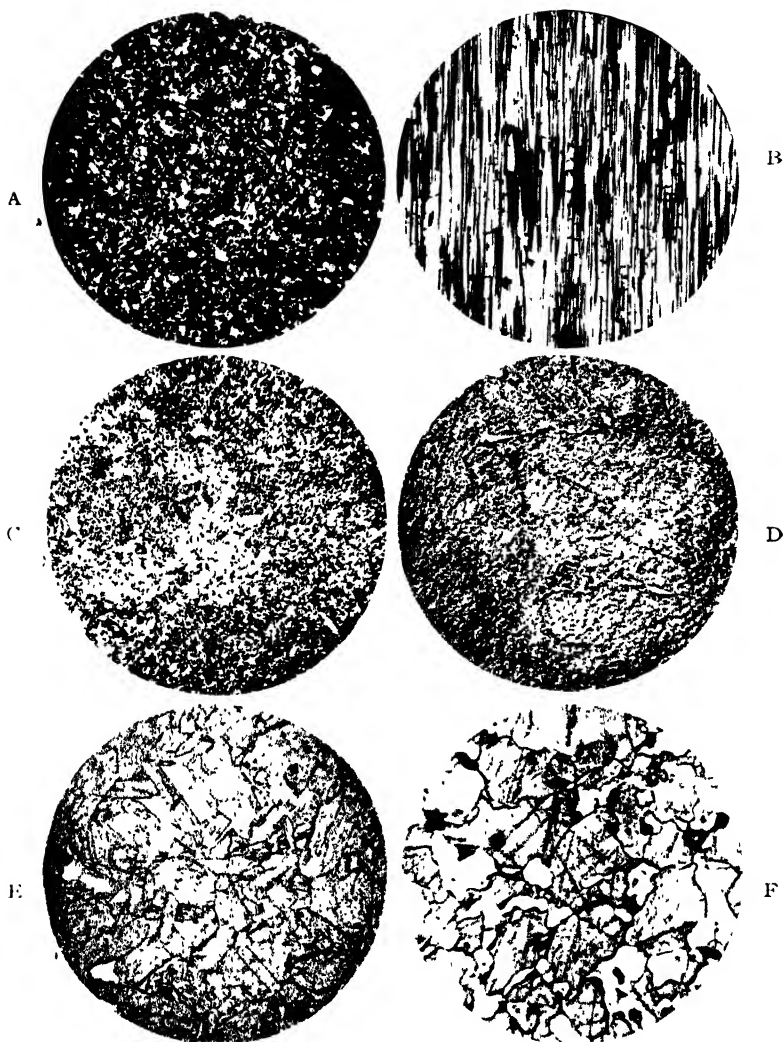
General Refs.

R. A. F. Penrose, *Journ. Geol.*, 18, 1910.

A. W. Grabau, "Principles of Salt Deposition." (McGraw-Hill Book Company, New York), 1920.

F. W. Clarke, "Data of Geochemistry." *U.S. Geol. Surv., Bull.* 770, 1924, p. 243.

G. W. Tyrrell, "Principles of Petrology." (Methuen, London), 1926, p. 232.



SULPHATE AND NITRATE

- A. Gypsum (Pe mian), Kirkby Thore, Cumberland ^N [x 25]
 B. "Satin Spar" (Fibrous Gypsum), Nottinghamshire ^{*} [x 25]
 C. Gypsum (Purbeckian) Sub-Wealden Boring, Sussex. ^N [x 15]
 D. Celestite, Yate, Gloucestershire [x 15]
 E. Barite, Patterdale, Cumberland. [x 14]
 F. Nitrate ("Nitratine"), Antofagasta, Chile [x 20]

[*Crossed Nicols]

CHAPTER XI.

THE PRINCIPLES AND PRACTICE OF DIFFERENTIATION AND CORRELATION OF SEDIMENTS BY PETROGRAPHIC METHODS.

The Geographical Cycle—Provenance—The Distributive Province—Relation of Sediments to Parent-Rocks—Conditions of Deposition—Technique of Application of Petrographic Methods—Schedule of Information to be obtained from Heavy Mineral Assemblages—Deductions from Records—Special Cases and Difficulties—Thin Section Correlation of Consolidated Sediments—The Study of Accessory Minerals in Igneous Rocks.

THE basic principles underlying the technique of differentiating or correlating strata by means of their stable mineral components are essentially those fundamental to the science of geology. No new or fantastic theories have had to be invoked to support their validity in this connexion or their use in this particular application to determinative stratigraphy.

These principles are practically all embodied in the modern conception of the geographical cycle, in its geological interpretation. Briefly stated, the cycle implies terrestrial uplift of a base-levelled or peneplained region; consequent reanimation of the forces of denudation; their slow operation in wearing down this newly-formed land-surface and the persistence of these forces until a new base-level is once more attained. The complete cycle is thus a geological episode and modern stratigraphy owes much to the recognition of these periodic recurrences. Expressed in another way, it is the alternation of geosynclinal and orogenic phases of earth-history.

Now this kind of cycle of geological events can, for our purpose, be broadly construed as a cycle of sedimentation. The newly uplifted land-mass, composed of igneous and/or sedimentary rocks, undergoes subærial denudation and from the very first incident of destruction gives rise to a new sediment. With continued disintegration of the mother-rocks there is

built up a collateral sedimentary deposit derived therefrom; so the process matures with the achievement of the base-level phase, assuming no interruptions of a diastrophic or similar disturbing character. Thereafter this newly-formed and, by this time, consolidated sediment itself becomes involved in orogenic movements and, probably rent and deformed with igneous intrusions, rises to initiate the next cycle of sedimentation.

Naturally the conditions under which such cycles are achieved vary widely under the influence of climate and the area of the earth's surface affected. We may contrast the normal cycle as outlined above with the arid cycle determined under desert conditions; also the results of upheaval of a comparatively restricted area of a continent with those accruing from a widespread orogenesis which, like the great Alpine movements, encircles nearly half the globe. In this work it is important to keep both such perspectives in view. But whatever the magnitude of the cycle under investigation, whether in space or in time, the simple principles which it implies constitute the foundation of our work and should be kept constantly in mind.

It is necessary to examine the component factors of the sedimentation cycle in further detail. First of all the newly uplifted land-mass; this, or the rocks of which it is composed, is essentially the *provenance* of the sediment formed by its denudation. The term *provenance* implies source of origin; but, in addition, it has been found convenient in petrographic work to introduce some qualifying definition which enables that source to be visualised as a geological entity. The term "Distributive Province,"¹ first introduced by A. Brammall, has been generally adopted and implies the environment embracing all rocks, igneous, metamorphic and sedimentary, contributing to the formation of contemporaneously accumulated sediment. It is essentially the rocks of the distributive province which, on weathering, yield up their minerals, the stable species to survive rigours of chemical reaction and mechanical transport, the unstable components to perish. The more diversified the rocks of the distributive province, the more variable the sediment

¹ In H. B. Milner, *Quart. Journ. Geol. Soc.*, 78, 1922, p. 366.

formed from it. In some cases the province may be entirely sedimentary; this implies that the sediment formed receives its constituents second-hand; in other words, it represents redeposition of a pre-existing sediment. By contrast, disintegration of igneous rocks furnishes primary sediments.

Conversely, accessory minerals of a sediment, sometimes individually, generally collectively, constitute a measure of its provenance, leading to a reconstruction of the nature of the distributive province even though all traces of this may long since have disappeared. This is because certain minerals or groups of paragenetic species are inferential of definite rock-types. Thus the reciprocal relationship between provenance and sedimentary rock is always kept in view in this work.

The next factor concerns the transference of released mineral matter from parent-rock to basin of sedimentary accumulation and the circumstances in which such transference takes place. Two important influences exert control; the mechanical agency or medium of transport is one; chemical destabilisation, the tendency of many rock-forming minerals to undergo decomposition when released by denudation, is the other. Mechanical forces, whether wind, water or ice, largely determine the ultimate physical forms of the derived mineral grains; to these forces such inherent properties of minerals as hardness, gravity, cleavage etc., react in different ways according to their fundamental molecular constitution; shape and size of mineral particles are likewise functions of them. Chemical weathering attacks the less stable rock-forming minerals, which are thus decomposed, formed into secondary products and dispersed in solution, finally to reappear in most cases as authigenic constituents. Every sediment bears the impress of this destabilising environment to a greater or lesser degree; it is essentially its sifting influence which tends to restrict the number of critical heavy minerals which survive, thus enhancing their indicative value.

Neglecting for the moment the time-factor required for this transference of material, it will be clear that successive phases of denudation will promote corresponding phases of sedimentation. If this is reduced to the mathematical conception of plane-surfaces, then we can imagine an infinite series of denu-

dation planes having their counterparts in equivalent sedimentation planes. Thus the accumulation of a given thickness of sediment will represent the destruction of a corresponding and directly related thickness of parent-rock.

Now if the original parent-rock is homogeneous in composition throughout the cycle of erosion, then it follows that a sediment equally homogeneous in composition will result, *ceteris paribus*. But if the parent-rocks vary in composition with progressive denudation, so the contemporarily formed sediments will indicate, by change of stable accessory minerals, such inherent variations of provenance; the sediments will, in fact, themselves exhibit mineral variation to a corresponding degree, which thus becomes characteristic of them. If there is definite mineral variation in a given thickness of sediment, then recognition of the degree of that variation and of the planes or horizons at which it takes place furnishes criteria of subdivision of that sediment. This, then, is the basis of differentiation of sedimentary deposits by means of stable, chiefly heavy mineral, variants.

It further follows that if these heavy minerals have any potential value as indices of differentiation or correlation of the sediments to which they are indigenous, they must, like fossils, have a reasonably restricted range in space and time, especially the latter. This depends again on the rocks of the distributive province; the more varied in mineralogical composition these are, the more definite and restricted will be the sedimentary mineral zones.

The comparison between detrital minerals and fossils, however, is a dangerous one and cannot be pushed far, principally for the fact that mineral species, unlike fossil species, do recur after temporary "extinction," similar groups of minerals reappearing time and again throughout the geological record, but, as will be shown, not in such a way as to vitiate their use in each special circumstance. Notwithstanding this, the simile is a convenient one providing it is not unduly stretched. Actually, mineral "zones" are seldom sharply defined; gradual transition (in a conformable series of strata) is the more general condition proved; this state of things is conveniently illustrated in the diagrams (*Figs. 91, 92*).

A, B, C, D, E and F (*Fig. 91*) represent different rock-types in two distributive provinces (1) and (2) respectively. The initial denudation of (1) and (2) starts, probably, with C and F respectively; the first types of sediment to be laid down (C' and F') will therefore have decided C and F affinities. As the drainage is cut back, B and E contribute material, the transition being marked by sediment with bC and eF affinities respectively (the smaller letter in each case denoting the lesser influence). With the progressive advance of denudation, both B and E assume importance, with the result that still newer deposits B' and E' are evolved. Similarly A and D contribute the deposits A' and D' respectively. Ultimately vertical sections in the

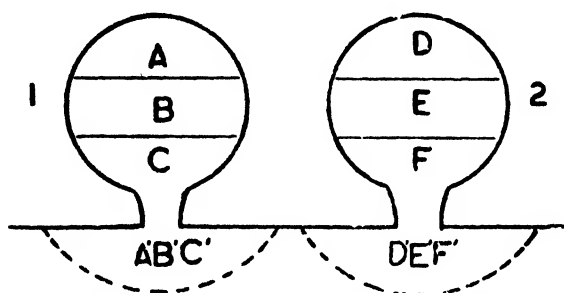


FIG 91. Distributive Province Diagram.

newly-formed deposits will disclose successions as indicated in the diagram (*Fig. 92*), bC', aB', eF' and dE' being the transitional zones from one horizon to another.

Contrasted with such vertical differentiation of sediments is the important and, in many respects, more difficult application of heavy accessory minerals to areal correlation, *i.e.* the comparison of these indices from place to place and assessment of their similarity or dissimilarity as a basis of correlating the sediments to which they pertain. Examples are furnished within limited areas by the comparison of samples from a series of wells on a given oilfield where, perhaps, only a few square miles of a formation are concerned; or over a much wider area, by comparison of samples collected from isolated outcrops or from different points across a long stretch of country. Whatever the area involved, however, the guiding principles are the same as before, with the addition of one uncertain factor: the

vagaries of spacial distribution of material. This requires explanation.

In the case of differentiating sediments in vertical succession as described, we are dealing with a restricted column of rock in which the chances are most favourable to the manifestation of every variation, however subtle or striking. With lateral correlation, a vast area has to be explored (comparatively) and variations which may or may not be entirely due to the influence of parent-rocks have to be taken into account.

So long as one fairly definite distributive province has been laid under contribution, the formation may be expected to carry distinctive mineral characters throughout its entire develop-

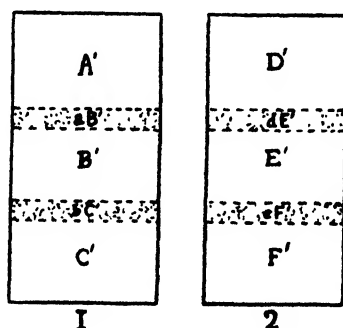


FIG. 92. Vertical Sections and Mineral Zones.

ment; comparison of samples from different places will tend to show mechanical rather than mineralogical variation. The reason for this is to be sought in the original distribution of material during the phase of sedimentation concerned. Now distribution is to a large extent independent of the nature and provenance of detritus and as it affects the present conception, it is not solely a question of mechanical agencies of transport. The actual medium in which the material is distributed is of equal importance.

Consider marine conditions. Distribution of sediment, apart from land-drainage, is controlled by the ocean, its currents and their directions; the width and configuration of the continental shelf; depth of water; magnitude of the sedimentary load; size of particle; physiographical factors, climate etc.

Along any one time-plane lithology may change rapidly; the stable "heavy" mineral supply may become impoverished; the grade-size of the sediment may diminish so considerably that recognition of an anticipated mineral suite may be almost impossible. Yet these are the conditions normally encountered.

Again, the conception of two or more distinct distributive provinces, contributing their quotas of material to sediment accumulating in a common basin, is very real; present-day examples of this are numerous; similar circumstances have clearly operated constantly in past geological history. Under such conditions there is continual intermingling of different mineral suites; at some stages one suite predominates, at others, another; equally there will be periods when each exerts a similar amount of influence. Or it may be that the drift of sediment, the product of one particular province, may determine intermingling with the product of another province geographically far removed, while beyond the zone of drift, the product of the latter province may occur exclusively. All three sediments co-exist in a common basin, the two distinctive products and their compounded elements in the "overlap" zone. They may clearly be contemporaneous in point of time and will probably be characterised by a common fauna throughout. It is essentially the mineral composition which will vary and, in such an example as this, to an extent which practically vitiates any correlation over large areas. It is for this reason unsafe to push the application of petrographic methods too far in areal stratigraphy and to this extent the limitations of the technique must constantly be borne in mind. The principles discussed in this connexion will perhaps be more firmly grasped by means of the accompanying diagram (*Fig. 93*).

This shows the prevalent current travelling in a direction from the first to the second province, parallel to the shore-line. While the sedimentary series $A'-C'$ would preserve local individuality, its lateral displacement due to the current would cause contamination of and interdigitation with the series $D'-F'$, indicated by the shaded area in the figure. Thus in specific cases the composition of the mixed sediments might be represented by $c'F'$, $b'E'$ etc., c' and b' connoting the introduction of material from the first province. Beyond the zone of mixing, sediments $D'E'F'$ preserve their fundamental charac-

ters; clearly the mineral composition of A'B'C' may be vastly different from that of D'E'F', yet assuming contemporaneity of deposition, they are theoretically correlative on any other grounds.

From this exposition of first principles, we may now turn to a consideration of the technique involved in their application. At the outset a word of warning is necessary. As in most other branches of specialised science, experience counts for everything. However well the theoretical aspects of the subject may be assimilated, nothing but complete mastery of the method and scope of investigation will lead to success. The first essential is proficiency in diagnosis of minerals as detrital

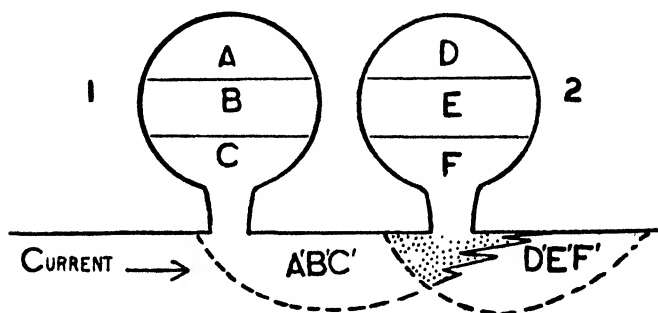


FIG. 93. Current-Action on Deposition.

grains. This will be found a vastly different proposition from familiarity with such minerals as museum specimens or constituents of rocks studied by means of thin sections.

The cult of the detrital mineral is well worth following; apart from its obvious application to problems in economic geology, its study opens up a wealth of interest, especially when the natural history of a sediment is the motive of the work. But it is necessary to begin at the beginning. Competent diagnosis of detrital minerals, from the ubiquitous quartz to the rarest species, springs only from continual study of examples from as many different sources as possible. Only in this way can the innumerable variations of detrital minerals be learnt and accuracy in application achieved.

The beginner is advised to procure for himself a set of microscope slides of the commoner sedimentary rock minerals

—concentrates of individual species—and to study these exhaustively. A good list to start on is as follows:—*quartz, microcline, glauconite, calcite, ilmenite, pyrite, leucoxene, tourmaline, staurolite, garnet, rutile, zircon, muscovite, biotite, kyanite, andalusite, topaz*. Two or three mounts of each species from different geological horizons should, if possible, be obtained and thus certain variations appreciated. The choice should also be made with a view to selecting concentrates of different grade-sizes, so that the minutest particles may receive as much attention as those of larger dimensions. In each instance learn the essential crystallography first. Study the normal crystal habits of the mineral with a good text book of mineralogy and then with the aid of the information detailed in Chapter IX of this book, work out the nature and degree of detrital modification.

To the science of crystallography many students do not hesitate to express a certain apathy; there may be something to be said for this, but the author hastens to assure the reader that it implies an intelligent use of the text book and an understanding of the elementary principles of the science, especially as regards the optical physics involved; “stereographic projection” and the higher mathematics of the subject are not necessary for this particular work; relieved of that, crystallography can be made a most fascinating study, doubly accentuated when it is correctly applied to the reading of mineral grains under the microscope.

From the study of individual mineral concentrates as suggested, procedure should be in the direction of detrital mineral suites isolated from well-known stratigraphical units. In this connexion a selection might appropriately be made from the Inferior Oolite, Corallian, Lower Greensand, one of the Lower London Tertiaries, *e.g.* Thanet Sands of the London Basin, the Bagshot Sand, Pliocene sand from East Anglia and any drift deposit; good examples of the latter occur in most of the plateau deposits of the home counties. Additionally an alluvial sand, a desert sand and a glacial sand should be obtained for the study of contrasted shapes of the particles in each case. With this as foundation, no time need be lost in proceeding to the more uncommon minerals, either studied as individual concentrates or as constituents of specific mineral assemblages.

Moreover, throughout the training, learn to exact the fullest powers of the microscope; on its efficient employment depends the difference between crude and really competent work.

The next stage is an attempt at differentiation of two well-known stratigraphical formations. Comparison of any two slides of the total heavy residues from examples above suggested will indicate at once the variations which serve to distinguish them. Those whose facilities do not extend to investigating British formations in this manner, are advised to choose any two well-known deposits in their area, preferably two separated by a considerable geologic time-interval; thereafter this interval should be gradually reduced until the investigations concern horizons in the same formation. It will probably be found that it is this phase of the work which presents the first real difficulties. Even the novice seldom fails to recognise essential differences between mineral suites of two widely separated (in time) deposits; it is the splitting up of a "straight sequence" of beds within one stratigraphical unit which calls for experienced observation and deduction.

From differentiation of beds in vertical succession, attention should be turned to a simple problem of correlation, say, the examination of a series of samples collected from isolated outcrops of a known formation, or from three or four outliers etc. A further valuable test is to trace the variation through a deposit along the strike over some distance (50 miles), keeping to a constant horizon either lithologically or, better still, palæontologically determined. This should be supplemented by similar work over wide outcrops in directions at right angles to the original shore-line.

Investigation of subsurface rock-samples is but a particular case of the technique of differentiation and correlation by accessory minerals, but with this important difference; whereas with surface work the rocks themselves, their lithology, developments and structures in which they are involved, are all exposed to the eye (and to this extent is their investigation facilitated), rocks studied by means of boring-samples may lie deeply buried under younger deposits or a thick covering of drift, hidden for all time, or possibly outcropping many miles away from the area concerned. This is especially the state of things prone to occur in oilfield geology wherein these petrographic

methods find one of their most valued applications. This kind of subsurface stratigraphical research requires the highest degree of skill in handling mineral residues for differentiating a vertical sequence of samples furnished by numerous oil-wells; in comparing them *areally* at known depths (correlation) so as to trace out the attitude of an important stratum; it also calls for intelligent and restrained deduction as a basis of defining subsurface structure.

The latter problem is frequently the most difficult of all. It cannot be too strongly emphasised that incompetent work with heavy minerals leads to disaster more rapidly than any other known weapon of attack in the geological armoury; a careless mistake in identification or an incautious interpretation of microscopical analysis may easily lead to costly error, a matter of no small moment in the economics of petroleum development. But perhaps of more importance is the harm done to the science by such slovenly work. Unfortunately, examples of this are not wanting and in more than one instance known to the author heavy mineral methods have earned a measure of opprobrium which they little deserved.

In petrographic methods biased to this particular line of enquiry, the personal equation looms large. No two operators work on precisely the same plan and what may appear to be subtle though convincing proof of distinction to one, may be passed over in favour of alternative evidence by the other. This, from the very nature of the investigations, is bound to be the case. In most branches of analytical geology there are more ways than one of arriving at the accepted conclusion. After all, the main thing is to achieve accuracy; the actual method of attaining it matters little so long as it is scientific and is fully justified by the principles laid down. The reader has only to compare different published accounts of heavy mineral analysis and correlation to perceive the truth of these remarks.

Accordingly, in such circumstances no hard and fast rules can be laid down in the actual process of differentiation and correlation by these methods, nor would the best interests of the work be served by any attempt to standardise technique. On the other hand, experience has taught a certain routine which has been found satisfactory and adequate to every problem worked out by the author. It has the merit of being

straightforward ; it does not imply an inordinate amount of time to achieve results ; it does not attempt the impracticable task of reducing mineral assemblages to mathematical formulæ ; and it may be claimed to be sufficiently elastic to meet every contingency in which the methods may be invoked. The reader will not go far wrong if he follows along similar lines ; doubtless, when he has acquired his experience, he will be able to make many improvements in detail.

Starting with the microscope slides of the minerals under investigation, two courses are open, according to the nature of the work. If it is to be exhaustive and time is not an important item, three slides per sample should be made. One of these is the original sediment, either in its natural state, if incoherent, or gently pulverised, if consolidated. The second is a mount of the cleaned, light sediment (*i.e.* S.G. < 2.9, usually the 85-52 sieve fraction (B.S.I., p. 88). The third is the total "heavy" residue. The object of this triplication is to safeguard against loss of any soft or soluble mineral during the process of cleaning the sample etc. Also, many instances occur where the light minerals are as important, if not actually more so, than the heavy constituents.

Where, however, previous knowledge of the sediment discounts the chance of the light minerals serving useful purpose, or where, as in much economic work, time is a vital factor, then the light and original mounts may be dispensed with and investigations proceed entirely on the basis of the heavy mineral residue. The operator must use his own discretion in the matter.

Triplication of slides necessarily implies much additional labour in preparation, but actual microscopical examination of the light crop and original sample takes only a fraction of the time occupied with the heavy residue. In the author's view, if the light minerals are neglected altogether, there is always the feeling that some important feature has been passed over, that the sudden influx of minute organisms, or minerals like feldspar or glauconite, has been missed, when any one of these components might have proved valuable.

The practice of isolating magnetic and non-magnetic crops of minerals and employing separate mounts for each, while often essential in academic research, may be found impractic-

able in economic work; the total heavy residue, or a proportionate part of it, is then the basis of comparison. It is often difficult to carry in mind the salient features of several assemblages when attempting their differentiation, especially if the number of samples is large, a difficulty much enhanced by duplicating every slide. This has reference entirely to economic work; as stated above, where time is no object and where the most detailed investigations are contemplated, circumstances are altered and even six slides of one sample, two high gravity concentrates in addition to original, light, magnetic and non-magnetic crops, may be essential. The author has had occasion to use a dozen mineral segregations (each involving special preparation and an equal number of mounts) from one concentrate in order to reach exhaustive quantitative and qualitative results from certain special samples.

The slides of the respective mineral residues to be examined are first sorted out in some definite order, according to depth (oil-well or water-boring samples), geographical or other position (field-samples), or in numerical order if there is nothing else to determine the arrangement. Next, every slide in succession is rapidly examined under the microscope, any striking similarities or dissimilarities being segregated at the outset into groups. [N.B.—It is convenient to use a series of cardboard specimen-trays, about 4 in. \times 5 in., to accommodate each group of slides.] The groups form the basis of subsequent methodical examination, leading to confirmation of the initial segregation and to further subdivision of the slides, hence of the samples they represent. The object of this preliminary "run through" is to enable one to grasp at the outset the main features of the mineral suites; much may be discernible in the process; it is seldom that it is not so. But at least a valuable first impression of the problem ahead is gained and for this reason, if for no other, this preliminary survey is desirable. To work diligently through, say, two hundred well-sample residues (by no means an uncommon job in an oilfield laboratory!) without any idea what the two hundredth is like until, at long last, it is ultimately reached, can prove a most disconcerting performance.

The following schedule of information is next sought:—

- (1) Identification of minerals.
- (2) Notification of minerals with special crystallographical features (other than accidental occurrences).
- (3) Notification of minerals with special physical features (other than rare occurrences).
- (4) Notification of minerals with special optical properties.
- (5) Relative frequency of occurrence of individual minerals.
- (6) Reciprocal relationship between two or more prominent minerals.
- (7) Grade-size or sizes of predominant minerals present.
- (8) Average shape of prominent (common) minerals present.
- (9) Any particularly striking feature (or mineral) sufficiently prominent to constitute an index of the sample concerned.
- (10) Character of total assemblage.

The schedule in itself looks somewhat formidable, but in actual practice the experienced operator checks up this information almost subconsciously and enters it on his record, at the same time carrying in his memory the salient features, of whatever nature, of any unique or striking assemblages examined. A facsimile of the form devised by the author for recording this information is illustrated in *Fig. 94*, p. 446.

For the benefit of the novice, the ten items in the above schedule are here annotated :—

(1) *Identification.* In view of what has already been written on this point, little remains to be added. Diagnosis can never be too thorough and the greatest accuracy is absolutely essential. In some cases, one hundred per cent. identification may be impossible, especially with very fine grade sediments; in other cases a problem mineral may present itself which defies positive diagnosis in the time or with the facilities at hand. If such a mineral is adventitious, occurring in one or two samples only, it may probably be neglected with safety; if it ranges through a number of associated samples in such a manner as to constitute a feature of those samples, then it is necessary to recognise it by some make-shift designation, *e.g.* "Mineral X." Ultimately, of course, the enthusiastic worker will not be content until he has found a mineralogical "value" for "X" (p. 189). A further point to note is that a mere list of mineral occurrences is *per se* seldom of much value; it is the

rest of the qualifying information, covered by the schedule, which determines its utility, a remark applying equally to mineral residues segregated from crushed igneous rocks (p. 474). For further aid in diagnosis, see p. 491.

There is no particular order in which minerals should be determined or recorded, though there is some convenience in listing light species first, followed by the iron-ores, then by the common non-opaque minerals, working down to the scarce occurrences at the bottom of the list. In published records, however, the arrangement of the minerals by crystal systems has much in its favour (p. 225).¹

(2) *Special Crystallographical Features* include well preserved crystals of a mineral (euhedra); striking development of subsidiary faces (e.g. the "facetting" of zircon); prominent terminations (e.g. acute bipyramids); twins (e.g. geniculate twins of rutile); also striations, zoning, inclusions and any obvious inherent structures. Any prominent varietal features of a given mineral traced through a series of samples may quite likely result in turning the scale in favour of their correlation. In other directions, varietal features of minerals have decided bearing on questions of provenance.² Inclusions, especially in quartz, are of value in determining parent-rocks.³ Even absence of crystallisation may, in some cases, prove a valuable characteristic of some prominent species.

(3) *Physical Features* amenable to microscopical determination concern chiefly colour, lustre and grain "morphology." Colour, or its absence, is an important criterion of identification. Colouring matter may be uniform or partial; for instance, some sapphire grains are uniformly blue, others from different sources have their colour dispersed in patches, giving a blotchy appearance. Parti-colouring (e.g. brown-green tourmaline) may prove a distinctive feature. Vivid colours are noteworthy since most detrital minerals exhibit somewhat subdued colouring. A definite coloured mineral, e.g. purple zircon, may prove a critical indicator of a deposit, equally of its provenance.⁴ A common mineral occurring in an uncommon colour would constitute a valuable index of the samples in which it was

¹ H. H. Thomas, *Quart. Journ. Geol. Soc.*, 75, 1909, p. 231.

² P. G. H. Boswell, *Mineral. Mag.*, 21, 1927, p. 310; also A. Brammall, *Proc. Geol. Assoc.*, 39, 1928, p. 48.

³ A. Gilligan, *Quart. Journ. Geol. Soc.*, 75, 1919, p. 260.

⁴ P. G. H. Boswell, *op. cit.*

found, *e.g.* naturally pink andalusite, green garnet. Lustre, determined by good artificial incident light, needs no stress here.

Grain "morphology" is a convenient expression to describe the external form of mineral-fragments. It is not merely a record of shape and size, though these properties could appropriately be classed in this category (see (7) and (8) below), but rather the structure of the grain, the contrast between acicular and granular developments, between fibrous and crystalline etc. Examples in which grain morphology has proved critical in differentiation are the temporary appearance of actinolite (fibrous hornblende) at one horizon of an amphibole-rich deposit; granular titanite as characteristic of a zone in a deposit otherwise marked by ragged, irregular grains of the same species; also the co-existence of spheroidal and irregular grains of siderite.

(4) *Optical Properties* of minerals, especially where they are of an unusual character or of pronounced development, are among the most important criteria of distinction. Refractive index, birefringence, pleochroism and the nature of the interference figure (if any) are the four most sought after features. Refractive index, as indicated by relative "relief" to the medium in which the minerals are mounted (usually Canada balsam), is probably the most important first impression in diagnosis. With practice it is surprising how closely this can be assessed from microscopical observations, especially if several different mineral species are present, some immediately known, others unknown until thoroughly searched. Birefringence is all important in diagnosis if it can be accurately determined on mineral grains; this, however, is not always possible with dense or deeply coloured grains. Normally pleochroic minerals vary considerably in intensity of pleochroism: this constitutes the criterion and many examples could be given. Among the best from the author's notebooks are the intense blood-red pleochroism of andalusite from the Cornish Pliocene; the vivid brown-green pleochroism of hypersthene from a Quaternary sand of Martinique; the deep mauve pleochroism of glaucophane from certain Miocene silts of Trinidad and Venezuela; the olive-green to slaty blue pleochroism of chloritoid from the Bridport Sands of Dorset. In each case

the striking colour-change distinguishes the mineral, which in turn distinguishes the samples in which it is found. The examples could be multiplied many times; some of the best minerals in which to anticipate unique or distinctive pleochroism, apart from those mentioned above¹, are the amphiboles, tourmaline and staurolite.

In the matter of interference figures, the maximum information obtainable from these depends on ability in their interpretation. The mere observation of uniaxial or biaxial character is seldom of more than slight diagnostic value; an exception is the occasional occurrence of undoubted biaxial zircon; this would certainly prove indicative of the samples in which it was found. The kind of optical research implied is well illustrated by A. Brammall's work on the Dartmoor brookite¹ and as demonstrated by that author, it connotes nothing less than careful optical measurements, observations of the behaviour of the figure, in particular its colour-bands, on rotation etc. Those who possess sound knowledge of optical physics know how to appreciate and to use this valuable weapon, not only for diagnosis, but for running down a mineral which, apparently normal and of no index-value, becomes critical on account of some determined optical peculiarity; lack of such knowledge renders the observation both empirical and mechanical and constitutes a serious disadvantage in this kind of research. Other examples of critical interference figures of detrital minerals from the author's experience are the comparatively large axial angle of some black mica ($\pm 30^\circ$) suggesting phlogopite (diagnosis not apparent from the mineral itself); very large axial angle in some muscovite flakes; some basal quartz grains which show abnormal "splitting" of the cross on rotation; the eccentric, partial interference figure of a deeply coloured epidote; the optical characters of brookite, axinite and titanite; certain varieties of topaz with smaller axial angle than usual and very prominent crimson colour-bands.

(5) *Frequency*. If there is still a mild "bone of contention" among petrographers, it concerns methods of estimating, still more of reporting, relative proportional occurrences of minerals in a given assemblage. All are agreed that frequency statements, if accurate, may have considerable stratigraphical

¹ See p. 255.

value. In work on differentiation and correlation of sediments, this value is unquestionable. The problem is, how to arrive at an accurate expression without depending too much on purely visual assessment or without going to the other extreme of counting grain by grain, truly a heart-breaking process. Unfortunately, it must be admitted that, despite all that has been written, the problem is very far from a generally acceptable solution.

Most frequency estimations are undoubtedly by eye, and after continual practice it is, in the author's opinion, possible to arrive at reasonable results, providing the grade-size of the suite is not too small. The finer the grade, the greater is the inaccuracy of assessment, assuming a good quantity of residue. Scanty residues in any case lend themselves more readily to accurate estimation and even counting is then not too onerous. But no two estimations by different persons ever agree. The author has in the past frequently tried this out with his classes of students and it is surprising what variations exist in apportioning powers. What is abundant to one, is merely common to another; the tendency to attribute predominance to opaque minerals, because they show up sharply against a white background, is another source of error. The conclusion is forced that, except in the circumstances of limited residues of large grade-size, estimation by eye is really inaccurate, therefore of little value.

At the other extreme we have the work of W. F. Fleet,¹ who, in the course of his researches into heavy minerals in rocks of the English Midlands, found that nothing short of counting the grains of a residue gave satisfactory results. He writes, ". . . to obtain accurate results that may readily be compared with those of other workers actual counting of the grains is considered essential . . . at first sight, a tedious task, but it has been found that, using, say, a 1 in. objective with an eye-piece giving a large field, and by employing a mechanical stage, it is not a difficult matter to traverse the whole width of a slide several times, counting every grain. According to the closeness with which the minerals appear on the mount it may be necessary to count the grains in anything from twelve to fifty fields, and the number of grains may range from 500 to 1,000 or even more."

¹ *Geol. Mag.*, 63, 1926, p. 505.

Many American petrographers also have recourse to counting and their work certainly confirms the findings of W. F. Fleet. The superiority of this method is unquestioned. Where reliable quantitative results of proportional occurrence of each species are demanded, nothing short of counting is likely to give satisfaction. In our special work, this is definitely the case where the fundamental mineral assemblages from different horizons of a formation are not rich in species or varied; where, in fact, the same minerals tend to occur throughout, and differentiation perforce rests on less obvious variations and on relative frequency of occurrence.¹ In cases where the mineral differences prevailing in two deposits are sufficiently striking, the frequency factor may assume less consequence and qualitative estimation by eye suffice. But since much work carried out decidedly necessitates some numerical expression of frequency, then it would seem that counting is inevitable.

Even counting, however, has its "snags." F. Smithson² has drawn attention to the significance of the manner in which heavy mineral concentrates are prepared, those made by panning not being identical with those obtained with bromoform, or again where panning the "light" material and completing the separation with bromoform is involved (see also p. 65). Actual experiments with heavy mineral counts made on samples from which concentrates had been prepared *with* and *without* the use of panning (using in all cases bromoform) showed that divergencies are much greater in practice than might be anticipated. For example, in one case a zircon and monazite (combined) count gave 80 per cent. when the concentrate was prepared by first panning and then bromoform separation, and only 56.1 per cent. when bromoform was used direct. Assuming the latter method to yield the true value, then the advent of panning gives a result 1.68 times too great!

When it is considered that panning is so frequently employed, either solely where conditions do not permit of heavy mineral separation, or as part of the process of concentration where bulk samples have to be reduced to manageable size,

¹ A good illustration of the use of relative frequency of heavy minerals to find the necessary criteria for differentiating one sedimentary deposit from another is given by D. R. Derry in his account of the Pleistocene beds of the Don Valley, Toronto, Ontario (*Journ. Sed. Pet.*, 3, 1933, p. 113).

² *Geol. Mag.*, 67, 1930, p. 134.

then it is abundantly clear that even percentage frequencies of grains are not comparable as between one worker and another *unless their modus operandi is identical*. As F. Smithson says, "So long as a petrologist always employs the same procedure it is probably safe for him to compare his estimates one with another. But if he changes his method or compares his estimates with those of petrologists who use different methods of separation, erroneous conclusions may easily result."

A. L. Dryden¹ has reviewed this technique from a critical and statistical angle. He has shown clearly that mere counting is not accurate because it expresses percentages rather than qualitative observations as to "scarcity," "abundance" etc. He rightly points out that the problem is first one of *sampling* error. If correlation of strata is to be based on relative percentage (heavy mineral) frequencies, then the assumption must be made that an *average sample* from the deposit has been initially obtained and that the heavy mineral concentrate prepared therefrom is typical of that sample. How often is this really the case? From a mathematical aspect, A. L. Dryden shows clearly that accuracy in heavy mineral counting increases as \sqrt{n} , when n =the number of grains counted, actually *less* than the total number of grains (heavy or light) mounted on the slide under examination. Thus, "if twice the accuracy is desired, 4 times as many grains must be counted; if 3 times the accuracy, 9 times as many," etc. "The law of diminishing returns" probably will make us content to count but a few hundred grains. Perhaps 300 will suffice for most ordinary work, and even then the accuracy will far transcend that attained by estimation." A. L. Dryden stresses the necessity that the worker should be cognisant of the errors inherent to such counting analysis and that a degree of accuracy must not be indicated or implied which is, *a priori*, greater than genuine. He deduces in one case, where a particular mineral composes 50 per cent. of the sample, that to achieve an accuracy of 1/10th of 1 per cent. which has been implied by certain published "counts," the colossal number of 454,950 grains would have to be counted! Thus 1 per cent. accuracy implies a count of 4,549 grains in a similar case, whereas a normal count (say 200 grains) implies only 5 per cent. accuracy.

¹ *Proc. Nat. Acad. Sci.*, 17, 1931, p. 233.

Variation in heavy mineral percentages in samples taken from different localities is obviously both possible and normal, hence counting grains to a recorded accuracy of less than 5 per cent. error is clearly a waste of energy. From this follows the logical manner of expressing frequency obtained by counting, *vis.* the apparent value 50 ± 13 per cent. From this it further follows that the petrographer must state the method he has used to arrive at his percentage frequencies and "that the reader will not be misled into assuming that, for example, 58.1% means 58.1%, when it might as well be 50 or 70%."

In a well-reasoned statistical essay on comparison of heavy mineral suites, L. Dryden¹ emphasises the distinction between "correlation" as implying synchrony of geological formations and determined by, say, palæontological data and "heavy mineral correlation" which, as he demonstrates, is "an entirely different concept, although the process may lead to results quite analogous to those attained by the use of fossils."

Heavy mineral correlation, he argues, must rest on comparison of one heavy residue with another and mere segregation of impressions into "like" or "unlike suites" is not enough. If such correlation is to be based on inspection of percentages (resulting from "counts") of heavy minerals in different samples, there must be some method of "seeing these relationships quantitatively."

"For what we really mean by 'heavy mineral correlation,' " says L. Dryden, "is that for two given rocks containing similar mineral suites, the net result is *as if* the distributive province, mode of transportation, environment of sedimentation and other factors had been the same in the two cases. Such a supposed concatenation of events leading to similar mineral suites we think of as more likely to have happened in the two places at the same time. And the closer the samples be geographically the more favourably we look on such a theory. The whole method, then, is based on the degree of similarity of mineral suites—great similarity leading to the inference that the same cause has been at work in the two or more samples and dissimilarity implying independent (and thereby, in a single basin of deposition, non-synchronous)

¹ "A Statistical Method for the Comparison of Heavy Mineral Suites." *Amer. Journ. Sci.*, 29, 1935, P. 393

origin. And yet we have no way of expressing similarity except by juxtaposing columns of percentages, looking from one to another, and announcing that the suites are "like" or "unlike."

From this, Dryden gives a formula for comparing such data, based on determination of the "coefficient of correlation," r , as follows:—

$$r = \frac{\Sigma(XY) - nM_xM_y}{\sqrt{(\Sigma(X^2) - nM_x^2)(\Sigma(Y^2) - nM_y^2)}}$$

where Σ is the sign for the summation of that to which it is prefixed, n is the number of pairs of percentages to be used, *i.e.* the number of mineral species, M is the mean of that to which it is prefixed, X is any percentage from one sample, Y is the *corresponding* percentage (*i.e.* of the same mineral species) from another sample under comparison.

But since the value r implies statistical and not geological correlation and since such values cannot be compared with one another as simple percentages (*vide* formula), a "coefficient of determination" must be used which is arrived at by squaring r . Thus used r^2 is capable of giving in terms of simple percentage an expression of the proportion of elements common to two samples. In an example given comparing two samples A and C, $r = .70$, hence $r^2 = .49$, which is the percentage of elements of A common to C; by subtraction, .51 is the percentage or fraction of elements not common to the two samples.

Arising from this consideration are the following chief points:—

- (1) r^2 with heavy minerals is generally large, having a value between .50 and 1.00. If no species are common to two samples (as exemplified) $r^2 = 0$; if some are common to both, r^2 will vary from 0 to a maximum possible value of 1.00 when percentages are identical.
- (2) Varietal features of one species (as often used for heavy mineral correlation) may be treated in the formula as separate mineral species. They thus increase the number of species used in the formula and affect the reliability of r (hence r^2).

- (3) Reliability of such a statistical method increases with the square root of the number of observations. Thus 16 observations (or mineral species) will give twice the reliability that 4 observations or species will give.
- (4) Closely spaced samples give for r (hence r^2) a large value with small probable error.
- (5) Where statistical formulæ, such as the above, are employed, this implies sufficient known related samples so that statistical comparison of unknown may be reliable and valid.

"As the number of samples increases, and as greater and greater information about them is learned in the field, numerical comparison becomes more and more important and wholly supersedes visual inspection in value."

The present author has purposely given some prominence to L. Dryden's thesis because in cases where frequency estimations depend on actual counting, there is no doubt that unless those counts are properly compared and interpreted, they can prove as ineffective and misleading as purely qualitative methods. Pursued mathematically, in such a way that a rational, statistical interpretation can be placed upon them, then such determinations at once assume a totally different character and deductions may be made, not only by the petrographer but equally by his reader, which will have some sound relationship to actual facts.

Counting minerals grains is only possible where (a) the number of residues is limited, (b) time is not an important factor and (c) results are not expected on the "mass-production" principle. Consider for a moment an example in one of many oilfield laboratories known to the author. Here, when at high drilling pressure, as many as 50 to 100 samples may accumulate from a few wells in one day; the field being a youthful one, structural interpretation is awaited impatiently and critical evidence is desired from each of these samples in the shortest possible time. Supposing the 100 samples to average 1,000 mineral grains each, this means counting no less than 100,000 grains. Translate this into daily routine as distinct from research with purely scientific motives and the task

becomes superhuman ; certainly few pairs of eyes could stand the strain long without material damage. The method has actually been tried under the exigencies of oilfield development in more than one instance known to the author, but it had definitely to be abandoned from the sheer impossibility of the individuals to cope with the mental fatigue involved.

As in most things, a compromise is possible. In those circumstances where time and all other conditions permit and where accuracy is urgent, counting should be adopted and a full statement of the method of preparation of the concentrates and of the limits of accuracy of the counts should be given ; further, a statistical basis of comparison should be employed wherever possible. In other less important cases, limit the count to, say, four to six chosen (and representative) fields and average the results. Where one person is continually responsible for the results and for any interpretation which may be placed upon them and where he feels himself sufficiently safe to adhere to the older and quicker method of eye-estimation, let him not be afraid to continue in so doing. He may draw some comfort from the fact that in economic work, where these methods are in vogue in many different centres all over the world, for every grain counted there are probably at least one hundred deemed only worthy of passing inspection.

In the matter of recording frequencies, almost every author seems to have devised his own method and there is practically no recognised convention. Broadly speaking, the various records fall into one of three categories : descriptive, graphical and quantitative.

The descriptive method recognises the use of such terms as "abundant," "common," "scarce," "rare," or "ultra-dominant," "dominant," "frequent" and so on ; qualifying adjectives, *e.g.* "very," "exceedingly" etc., are from time to time added to raise or lessen the status of a mineral by a slight amount in the frequency scale. The trouble with such terms is that different authors interpret them in different ways ; while everyone may read an unequivocal meaning into two antipathetic expressions such as "rare" and "abundant," it is certainly not so easy to decipher the intended significance, or the actual fact underlying "scarce," "very scarce," "rare," "exceedingly rare" applied to a mineral in a range of samples.

In the original volume of this book, the author suggested the use of some of these terms as in the accompanying table. At the suggestion of W. W. Watts, each word or symbol was given a number, ranging from 9 downwards, as the mental picture conveyed by comparison of figures rather than of letters of the alphabet is a decided advantage for correlation purposes.

Term.	Symbol.	Proposed Number.
"Flood"	F	9
Very Abundant	A	8
Abundant	a	7
Very Common	C	6
Common	c	5
Scarce	s	4
Very Scarce	S	3
Rare	r	2
Very Rare	R	1

This scheme also embodied the use of the term "flood," implying the occurrence of a particular species so far in excess of all others as to constitute almost a pure concentrate. P. G. H. Boswell¹ has pointed out that "The indication of relative abundance by means of numbers seems first to have been introduced by E. Artini,² whose scale ran from 1=very abundant to 10=very rare. Later F. Salmoiraghi³ reversed the order and used the following scheme: 1=exceedingly rare; 2=rare; 3=very scarce; 4=scarce; 5=frequent; 6=very frequent; 7=abundant; 8=very abundant; 9=dominant; 10=ultradominant." P. G. H. Boswell himself follows this latter scheme.

Another method in vogue with some authors is the use of capital letters, small Roman letters and italics to denote extreme abundance, abundance and scarcity, respectively. Applied to complete mineral composition in the "light" and heavy groups, G. M. Davies remarks,⁴ "Owing to the small percentage of heavy minerals, however, one of them may be marked as 'abundant,' though actually scarcer than a 'scarce' mineral of the lighter group." Thus this simple method also has its drawbacks.

In the graphical method, which has not found general favour, relative frequency is represented by horizontal bars,

¹ *Quart. Journ. Geol. Soc.*, 79, 1923, p. 226.

² *Riv. di Min. and Crist. ital.*, 19 (1898), p. 33.

³ *Rendic. Ist. Lomb. Sci. Litt.*, 40, 1907, p. 870.

⁴ *Proc. Croydon Nat. Hist. Soc.*, 1915-16, p. 81.

one bar denoting rare, two bars common, three bars abundant (*Fig. 95*). The result works out as in the accompanying table. It represents but little, if any, advance on the descriptive method.¹

The quantitative method is simply the expression of frequency results as actual percentages and implies comprehensive counting of the grains as previously described. Such percentages are clearly the only logical mode of expression if counting is carried out. In America this has already reached the stage of convention; in this country we owe its exposition principally to W. F. Fleet.²

Thus from all these methods of determining and recording frequency, the reader has a wide choice, depending on the class of work in hand and on the degree of accuracy aimed at. The

	A	B	C	D	E	F	G	H
Garnet	—	—	—	—	—	—	—	—
Spinel	—	—	—	—	—	—	—	—
Magnetite	—	—	—	—	—	—	—	—

FIG. 95. Graphical Method of Expressing Frequency. The letters denote localities.

author's method is to count and express as percentages where special problems and time allow and to use the "9 to 1" convention in other circumstances, *i.e.* in routine work, without worrying very much what each numeral stands for so long as it is understood that "9" implies quantity, "1" rarity, at each end of the scale. Or, in some cases, the record of a mineral may be marked with an asterisk (*) and where, on account of abundance or for some other noteworthy reason, it is deemed necessary to stress it, the asterisk is underlined thus: *. This is a useful method when time is strictly limited, or where more definite expressions of frequency would avail but little in the work.

(6) *Reciprocal Relationship* between two or more prominent species is not an invariable nor an infallible test of distinction, though some interesting examples can sometimes be worked out. For instance, the relative abundance of red and yellow rutile is quite a constant factor for certain beds in the Northumberland Millstone Grit; other examples are the brown-

¹ E. Neaverson, *Proc. Geol. Assoc.*, 36, 1925, p. 252.

² *Op. cit.*, also *Proc. Geol. Assoc.*, 38, 1927, p. 4.

blue/tourmaline ratio; (a), (b) and (c) types of zircon (where (a), (b) and (c) represent distinct developments); the ilmenite-leucosene ratio; P. G. H. Boswell mentions "a reciprocal relation in the matter of relative abundance appears to exist between sphene on the one hand and anatase and brookite on the other" in connexion with the Upper Lias sands of the west of England.¹

Clearly such a reciprocal factor depends for its definition on actual counting; where there appears some chance of establishing it for a given set of beds, or even for a definite horizon, the attempt should be made, since this factor will tend to be an index of that sediment and will consequently have differentiating value. It will be noted that this information constitutes a special case of frequency determination and therefore requires the same cautious procedure and deduction as are necessary in that connexion.

(7) *Grade-Size* of predominant minerals is a matter of very great importance and frequently is of much consequence in the grouping of samples. Methods of arriving at this factor are described in Chapter IV. Both average grade-size of total mineral assemblage and grade-size of one or more predominant species may be used as indices of samples in which this factor seems likely to afford a basis of identification; though it must be remembered that change of grade, even abrupt, is not in itself evidence of change of horizon or of formation. Rapid and local lateral variation of facies will thus tend to confuse the issue.

It is relevant to mention here that comparison of total sand-grade (p. 85) through a suite of samples may be useful in their grouping.

In the matter of size of individual grains, this is often a valuable index, especially where one mineral overshadows all others in this respect. Mica is especially liable to occur in grains from two to four times the dimensions of its associated species. A series of topaz grains, of uniform dimensions 0.2 mm.-0.3 mm. in an assemblage of much finer grade, furnishes another example. Garnet, kyanite, sillimanite and occasionally hornblende, may each occur in similar circumstances, as other species. Finally, it is useful to determine percentage of heavy mineral per grade size and compare

¹ *Geol. Mag.*, 61, 1924, p. 257.

samples on this basis. The application of logarithmic moments to size frequency distributions in sediments has been described by W. C. Krumbein.¹

(8) *Shape* of minerals enters into comparative diagnosis of samples to a great extent in many problems of correlation. Some residues, *e.g.* from æolian deposits, are so conspicuously "rounded" as to render this factor alone decisive in grouping the samples of which this is a characteristic feature, when residues of contrasted "angularity" are among those investigated. An unconformity involving æolian beds resting upon aqueous deposits, or *vice versa*, is an example of this. Where "subangularity" is the observed feature, shape will probably be of little determinative importance. On the other hand, decided "angularity" of grain, in appropriate and contrasted shape-association, is of index-value; for instance, ice-borne deposits frequently exhibit this to a marked degree and may thus be individualised.

Shape of mineral grains is always taken into account in correlation, whether it prove of direct or indirect value; some workers even go so far as to estimate percentages of "rounded," "subangular" and "angular" grains of one common species, *e.g.* zircon, if this happens to occur in requisite variety of shape, but in the author's opinion this is seldom likely to supply data commensurate in value with the effort put forward in their acquisition.

(9) *Prominent Features* of detrital minerals, such as constitute *per se* indices of the samples in which they are recognised, often occur and prove invaluable in petrographic methods of correlation. In this category we place not only particularly striking minerals, but also *any* special feature of one or more species which is sufficiently notable to be utilised as an index. Examples of this include sponge spicules, shell-fragments, nodular pyrite, bipyramidal quartz, dolomite rhombs, large mica flakes with included iron-ores, prevalence of (010) kyanite flakes (with straight extinction); magnetite octahedra (*Fig. 83*); knee-shaped twins of rutile; *foraminifera* chambers filled with pyrite and so on. Anything, in fact, which is characteristic and persistent, also somewhat uncommon, is of value in a residue and should be utilised accordingly.

¹ *Journ. Sed. Pet.*, 6, 1936, p. 35.

(10) *Character of Total Assemblage.* In the hands of the experienced operator, a glance at the heavy mineral assemblage isolated from any particular sample, is sufficient to impress its essential characters almost subconsciously; many of the foregoing details are automatically assimilated in shaping assessment of the whole and in the course of examination of a series of assemblages, certain striking accordances and discordances are noted mainly on cumulative evidence; thus correlation and differentiation proceed, guided to no small extent by successive impressions of assemblages.

This grasp of essentials, to which reference has before been made, is really the basis of both rapid and accurate work; it is unquestionably the reward of experience and careful observation; this "assemblage sense" should be cultivated by all serious students of the subject.

To illustrate, many workers on British sediments are familiar with and can recognise at a glance, the source of origin of a particular heavy mineral suite; this is not an extravagant claim. Such characteristic assemblages of minerals obtained from the Inferior Oolite, Lower Greensand, Thanet Sands (Eocene) and Pliocene deposits, are self-evident to those who have investigated these and many other sedimentary rocks from different geological horizons.

It is not easy to put into mere words the significance of the character of an assemblage or the criteria by which that significance may be appreciated and made use of; instinct plays a large part in the technique. But those who take the trouble to master the above data may be sure that their grip on this aspect of the subject will be firm and lasting and that this new knowledge of sedimentary deposits will reveal many unsuspected features tending to individualise particular formations.

From the schedule of information above described, is deduced certain evidence vital to correlation problems, also to the wider questions of natural history of sediments and kindred palæogeographical data (Chapter XIII). For present purposes, the desiderata are as follows:—

- (1) Lateral and vertical persistence of minerals.
- (2) Definition of zones in vertical sequence.
- (3) Areal correlation and differentiation.

(1) The lateral persistence of individual minerals connotes their uniform or sporadic distribution and is an important factor, especially in problems of areal correlation. Such per-

FIG. 96. PERSISTENCE DIAGRAM

Localities	P	Q	R	S	T
<i>Minerals.</i>					
Magnetite.					
Ilmenite.					
Garnet.					
Tourmaline.					
Staurolite.					
Epidote.					
Biotite.					
Leucoxene.					
Zircon.					
Kyanite.					
Anatase.					
Rutile.					
Topaz.					
Andalusite.					
Spinel.					
Sillimanite					
Titanite.					

sistence may be expressed in terms of distance from one locality to another, or in the case of a small area where quarries, pits or well-borings yield the evidence, for example, from point to point as dictated by circumstances. It is desirable to construct

a persistence diagram for reference in this connexion and further to estimate the percentage of species which is actually persistent throughout; if this percentage is high (say over 60 per cent.) such an estimate may be of great significance. *Fig. 96* shows the type of persistence diagram usually employed. In the diagram a suite of minerals is shown in the left-hand column and the letters P, Q, R, S and T may be interpreted as different localities, oil-well horizons etc. Other published examples of lateral persistence diagrams are to be found in the references below.¹

The vertical range of a mineral or series of minerals tends to demarcate a zone or group of beds in a formation and a vertical range diagram is sometimes useful in recording such distribution. An example of this type of persistence diagram is given by A. Heard and R. Davies in their paper on the minerals of the Old Red Sandstone.²

(2) It follows from what has been written that any peculiar properties of minerals isolated from a sedimentary deposit not only individualise the minerals themselves, but extend to that deposit a definite factor of identification. The narrower the limits within which such peculiarities are confined, the greater the possibility of demarcating zones characterised by particular mineral associations or features. As previously explained, differentiation of strata in vertical sequence depends on the narrowing down of these limits, on the separation of one group of beds from another by means of indicative mineral species or assemblages. This naturally follows from a close examination of any series of samples taken from selected intervals in a given sedimentary sequence, along the lines already laid down.

(3) This phase of the work has been explained. It depends on careful comparison of samples taken from different points over a given area. The main possibility of error here is in minimising or neglecting the lateral variation natural to the deposit, an error tending to increase with the distance over which the work is prosecuted.

Such lateral variation usually implies lithology, *i.e.* grade-size of rock-particles, but it may also imply slight changes in

¹ H. B. Milner, *Quart. Journ. Geol. Soc.*, 78, 1922, p. 365; C. Raeburn and H. B. Milner, "Alluvial Prospecting." (Murby, London), 1927, p. 79, 81; H. H. Thomas, *Quart. Journ. Geol. Soc.*, 65, 190, p. 240.

² *Quart. Journ. Geol. Soc.*, 80, 1924, p. 508.

mineral composition. In comparing a series of samples taken from a formation over a given area, one may confidently anticipate a "fundamental mineral suite" which will identify the deposit as a whole and which will serve to establish relationship between them. The great thing to guard against is stretching comparisons too far; it would be foolish to attempt to "correlate" rocks of presumed similar age occurring in two widely separated regions such as Britain and the South of France, for instance, at least by petrographic methods. Any such attempt or its equivalent would naturally prove abortive of results of any scientific value. On the other hand, the author has often been asked to define the limits of areal correlation; this is again impossible, since it must vary in every area in which the work is undertaken. Only a knowledge of the fundamental geology of the particular country in view can act as a guide; but a safe rule is to err on the side of restriction, or if circumstances suggest that investigations over large areas or great distances are warranted, feel out from one locality to the next with the greatest caution, being constantly on the *qui vive* for abnormalities brought about by the overlapping of two distinctly contributed sediments, or by other complex and fundamental conditions of deposition. The student will soon learn what is practicable and what is not and no point would be gained here by any attempt to set a boundary to the work behind which procedure may be straightforward, beyond which it is fraught with difficulties and pitfalls.

Special Cases in the Application of Petrographic Methods to Correlation and Differentiation Problems.—

There are certain cases where the natural conditions of a sedimentary deposit render it necessary to take special precautions against mistaken interpretation, or where inherent difficulties are raised in the course of investigations. The most important of these will now be dealt with.

Unconformities. P. G. H. Boswell has remarked that "unconformities are usually emphasized by the changes in mineral composition, and these support palæontological and field evidence."¹ Generally speaking this is true; but frequently local erosion has been such, that what is theoretically

¹ *Geol. Mag.*, 1916, p. 164.

conceived as the plane of unconformity, is in reality a zone of unconformity, *i.e.* an indefinite thickness of sediment, the combined product of contemporaneous erosion and deposition, with a mineralogical composition having affinities with both the older and the younger deposits.

If a series of samples is taken laterally from the points 1, 2, 3, 4 (*Fig. 97*), the material collected will be from a "mixed" zone (dotted) and the mineralogical composition may be represented as follows:—

Sample 1.....ap.	} The small letters are indicative of transitional variations in composition from A to P, B to P etc.
Sample 2.....bp.	
Sample 3.....cp.	
Sample 4.....dp.	

Accordingly, lateral variation at approximately the same horizon becomes pronounced in these circumstances and where

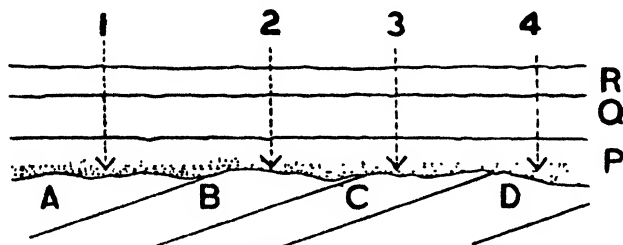


FIG. 97. Heavy Minerals and Unconformities.

such a structure is hidden (as it may well be in petroliferous territory which is being explored by the drill), a false impression can easily be drawn from discordances between the "heavy" residues, structural interpretation suffering in consequence.

The mitigating factor in this case is the tendency for "flooding" of a particular species to occur wherever different beds are subjacent to P and consequently the four samples may each present this feature and thus furnish a clue to the true state of affairs. The reason for such a tendency to "flooding" is that the actual process of differential erosion of the tilted edges of A, B, C and D tends to eliminate the less stable and gradually concentrate the more stable minerals in any undulations created; the material then becomes mixed with newly deposited sediment and in this way not only is the "mixed" zone initiated, but the proportion of "heavy" minerals greatly

increased, with probable concomitant "flooding" of one or more species. It is a noteworthy fact that such "flooding," especially of minerals like zircon, epidote, mica, tourmaline, garnet, rutile etc., is often characteristic of sediments involved within the zone of unconformity.

Current-Bedding. This feature, if developed on a large scale, may prove one of considerable difficulty in using heavy minerals for tracing out horizons. Flooding of the heavier species, much mixing of grades, even of distinctive mineral residues, or the influence of "gravity sorting" may prevail. If the investigations concern out-cropping rocks, some attempt at the resolution of the current-bedding into its components should precede any work on the sediment itself. But where a current-bedded deposit is being drilled and the only evidence available is from well-samples, then the problem becomes an exceedingly complex one, in certain cases impracticable of solution by petrographic methods alone.

Generally, however, it is possible to establish the fundamental mineral suite characteristic of the deposit, irrespective of the amount of disturbance it may reveal and to this extent one current-bedded formation may be differentiated from a subjacent or superincumbent deposit of different age, or from one unaffected by such false bedding. But any attempt to delimit mineral zones within such a formation is likely to be frustrated very soon; none but the broadest distinctions can be drawn in these circumstances.

In the study of current-bedded rocks over wider areas, the difficulty increases with the vagaries of the deposits themselves; lateral variation both of minerals and of grades is characteristic and difficult to follow through, unless the exposures are really good and continuous. Under subsurface conditions, detailed work is practically impossible.

The author's investigations of heavy minerals in current-bedded formations reveal the following tendencies which may be helpful in guiding the reader in similar cases:—

(a) In any set of inclined beds, *i.e.* to the general horizontal stratification, the finest material (grade) occurs at the downward end (bottomset planes) and contains the greatest quantity of heavy mineral (*Fig. 98*).

(b) The greater the angle of inclination (never more than

41° according to M. J. O. Thoulet), the greater the quantity of heavy mineral at the downward end; flooding of iron-ores characteristic.

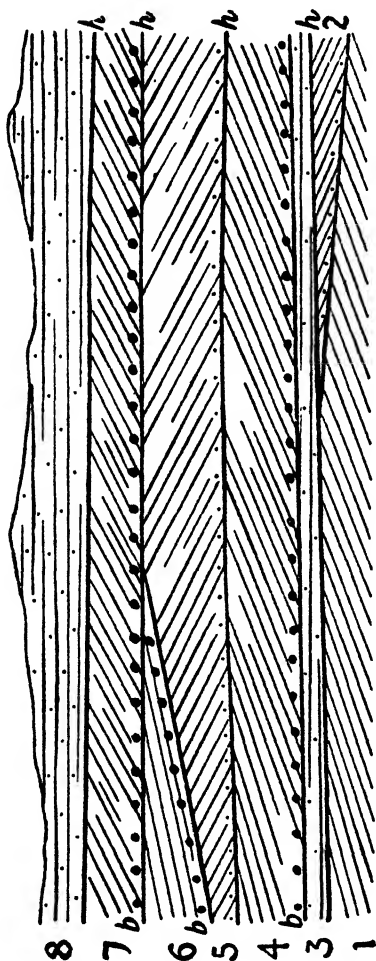


FIG. 98. Heavy Minerals and Current-Bedding.
General horizontal stratification represented by planes *h*; bottomset planes containing greatest quantity of heavy mineral, *b*. Beds 1, 4, 6, 7, indicate directions of prevalent current-trend; beds 2, 5, show discordant direction, with less heavy mineral; beds 3, 8, indicate approximately horizontal stratification (undisturbed deposition), with evenly distributed heavy mineral.

(c) In coarse sands the heavy minerals tend to be more evenly distributed throughout the inclined beds, though segregation of the heaviest constituents at the bottomset end is likely to occur.

(d) The largest yield of heavy mineral from current-bedded sands is obtained from steeply inclined beds of local development, *i.e.* where one set of beds occupies a matter of some few yards in actual horizontal distance. Gently inclined beds traceable over several yards on the whole yield less mineral residue.

(e) Beds which lie in a general definite direction, *i.e.* prevalent current, yield the greatest quantity of mineral residue, also the "basic suite" of the deposit; beds lying discordantly to that prevalent direction tend to be restricted in yield and frequently exhibit mineralogical abnormalities.

(f) Horizontal beds intercalated with inclined beds usually give mineral residues characteristic of the deposit as a whole.

(g) In æolian deposits current-bedding is liable to be much more confused and irregular in major direction than is the case with water-born deposits; consequently mineral distribution tends to be quite haphazard. Heavy mineral in these circumstances often congregates in pockets, representing the lee-side deposition in local dune-formation. In other words, where the beds give evidence of dune characters, as is often the case with æolian sands, the gentle inclinations are the planes with least heavy mineral, the steeper inclinations, especially towards the bottomset ends, being more profitable in this respect.

(h) Both current-bedding and ripple-marking developed in beds of geological age, tend to reproduce the same conditions of natural mineral concentration as are encountered in modern shore and æolian deposits, *i.e.* the heavy mineral being naturally segregated from the lighter.

Transgression of Chronologic and Lithologic Planes. The theoretical progression of lithological facies laid down on a continental shelf is from coarse to fine material, the grade-size of the constituent particles decreasing with depth of water in which they are deposited. This conception normally assumes a static condition of the sea-floor. Frequently, however, contemporary oscillation, gradual upheaval or subsidence of the basin is manifest, with the result that interpretation of the record of sedimentation from the subsequently consolidated deposits is apt to be erroneous if formulated on purely lithological grounds.

The transgression of time-planes, *i.e.* successive phases of sedimentation or bedding planes, by lithologic planes, *i.e.* suc-

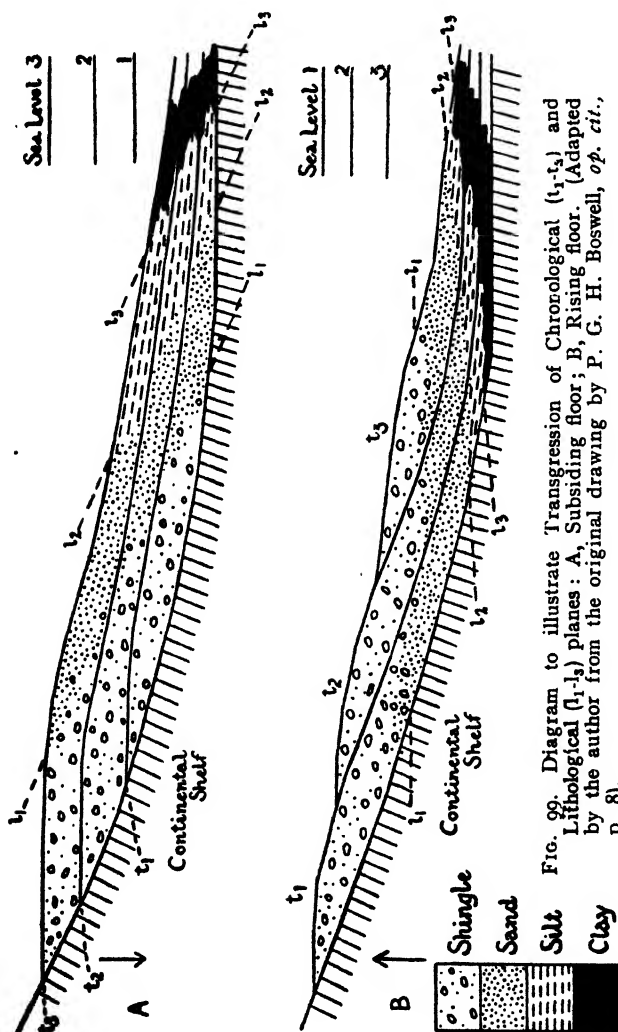


FIG. 99. Diagram to illustrate Transgression of Chronological (t_1, t_2, t_3) and Lithological (l_1, l_2, l_3) planes: A, Subsiding floor; B, Rising floor. (Adapted by the author from the original drawing by P. G. H. Boswell, *op. cit.*, p. 8).

cessive facies of deposition, is a direct result of one or other of those movements operative during sedimentation and the significance of this phenomenon has been discussed by P. G.

H. Boswell.¹ In the case of subsidence, the vertical thickness of the deposits is accentuated, while in the case of elevation, the lateral or seaward spread of the detritus is increased. In both cases definite facies such as sands, silts and clays are in juxtaposition when traced from one time-plane to another, so that ultimately when the deposits are consolidated, the tendency is for them to be differentiated on lithological grounds as true bedding planes, which is obviously fallacious. *Fig. 99* will serve to make this clear.

In tracing the mineral assemblage characteristic of the clay facies, for example, a variation will tend to occur in the residues as each successive time-plane is traversed, so that lateral correlation of the clay will be a matter of considerable difficulty. If, however, comprehensive sampling of the sand and silt grades associated with the clay is carried out, careful observation will detect a mineral suite characteristic of and common to the sand, silt and clay components of each successive time-plane and thus a clue is afforded to the real state of affairs. It is essentially the tendency of an inherent mineral assemblage to persist throughout a definite phase of deposition (involving change of lithological facies with progressively deeper water), that makes possible a correct interpretation of the true sequence of events.

A concrete example of this transgression of time and lithologic planes is furnished by the Upper Lias—Lower Inferior Oolite Sands of the West of England. These sands occurring at different localities between the Dorset coast and the Cotteswold Hills have been proved by S. S. Buckman to vary in age from place to place, the time or specific ammonite planes transgressing the lithologic developments. P. G. H. Boswell deals with this lucidly in the paper cited and with the relevant petrology in a more recent publication.²

Similar complications may be anticipated in any sediments deposited under conditions in which oscillation of the basin has occurred concurrently with deposition and examples are being constantly furnished during the course and geological development of various Tertiary oilfields in Asia and elsewhere.³

¹ *Trans. Liverpool Biol. Soc.*, 35, 1921, p. 5.

² *Geol. Mag.*, 61, 1924, p. 246.

³ L. B. Stamp, *Journ. Inst. Petrol. Tech.*, 13, 1927, p. 21.

Impoverishment of Heavy Minerals. Sedimentary rocks which, from their lithologic character or circumstances of their origin, are deficient in heavy mineral, may present obvious difficulties in the application of these principles. In this category fall reconstituted sediments, very fine clays and most organic deposits.

Where sediments are composed chiefly of the "*remanié*" minerals of pre-existing sediments, both quantity and quality of accessory species are liable to suffer. The monotony of a uniform and restricted mineral suite, confined for the most part to such stable minerals as the iron-ores, tourmaline, zircon, garnet etc., persistent through many hundreds of feet of strata, equally prevalent when the same rocks are followed out over large areas, renders subdivision on a petrographic basis very difficult, if not impossible in some cases. None but the broadest distinctions can be made, while comparison of samples from place to place, because of this constancy in composition, leads only to generalisations, not to define criteria of equivalent horizons. Obviously there is little to be done in such circumstances; where the very indices on which we rely are lacking, other methods must be sought. On the other hand, these cases are, in the author's experience, the exception rather than the rule and even in known reconstituted sediments such as the Wealden of England, differentiation within the formation is possible by means of heavy minerals (p. 484) and areal comparisons can be made with safety. In this instance it is attention to detail which matters.

With clays, given plenty of raw material to work upon, a reasonable amount of heavy mineral can usually be extracted, except from the very pure varieties. The trouble is obviated when dealing with outcropping rocks by the collection and treatment of large quantities of material; similarly with shales and other argillaceous types. It is when samples are meagre, as in the case of many oil-well samples, that the difficulty is intensified and the utmost effort has to be made to obtain the maximum quantity of raw material which existing sampling apparatus can provide. In these days the advent of the core-drilling has done much to overcome this difficulty.

Limestones and similar organic rocks yield heavy mineral in proportion to their impurity; the purest types, *e.g.* chalk,

are notoriously sparse in detrital constituents. In such cases recourse must be made to acid solubility or chemical factors as a basis of comparison (p. 192), though it is seldom that such rocks are not amenable to treatment by the more precise palæontological methods. Admittedly chalk is an extreme case and with many limestones it is surprising how much insoluble heavy mineral concentrate can be extracted by efficient methods, especially the centrifuge, as described on p. 67.

In the matter of saline deposits, including gypsum etc., research has shown that detrital mineral constituents are in a few cases recoverable and can be used with advantage; also types of mineral crystallisation are frequently invaluable in this connexion and should be studied accordingly. Structures revealed from thin sections of these massive mineral deposits are often of definite value as indices of certain developments at particular horizons and are accordingly admissible as evidence. This aspect of the interpretation of thin sections may now be reviewed.

Thin Section Correlation of Consolidated Sediments.—

The advent of core-samples of compact rocks in subsurface work has enhanced the possibility of differentiating between samples or correlating them by means of a microscopical study of thin sections cut therefrom, more particularly in the case of argillaceous and calcareous rocks. Hitherto, even comminuted limestones have proved, in the absence of other evidence, difficult to study from well-samples, the usual method being a quantitative comparison of inorganic (detrital and authigenic) material segregated by solution of the organic mass in acid.

In many oilfields calcareous rocks are a feature of the productive zones; sometimes such rocks are sufficiently individualised and developed to offer no occasion for doubtful recognition from one well to another; on the other hand, where the sequence is made up of alternating limestones with shales etc., identification and differentiation of successive horizons may be a matter of considerable structural moment, though furnishing a problem in specific identification of no mean difficulty. It is here that the thin section, studied from a particular angle, may prove of considerable value.

Investigation of several different limestones, both British and foreign, leads to the emphasis of essential morphological

differences between types, quite apart from mineralogical and palæontological variation. For instance, a shelly limestone (so-called) exhibits fragmental remains of the larger fossil shells of all kinds set in a definitely or indefinitely formed matrix, *e.g.* calcareous mud associated with iron compounds, sand, argillaceous matter or even volcanic detritus: at all events a matrix rendered conspicuous by its contrast to the main fossil-fragments and by its particular design, whether uniform or haphazard. Without identifying the fossil remains themselves, or testing microchemically for the type of carbonate composing them, an examination of the relationship of the larger to the finer constituents, *i.e.* the fundamental structure of the rock, may lead to recognition of certain morphological characters common to that rock within a limited lateral and vertical development. With a compact limestone in which no large organic components are apparent, the nature of the calcite or dolomite mosaic, the degree of crystallisation achieved or, alternatively, of mutual interference between the crystals, the manner of dissemination of secondary silica or iron compounds, and so on, may determine individuality whereby a particular example may be recognised. Oolitic, pisolitic and other special types of limestone may also be investigated from this point of view. Where the organic remains present can be identified, *e.g.* algal, foraminiferal, polyzoan, bryozoan, coral and other types, obviously the possibility of linking up similar samples is still further enhanced (p. 394).

Similarly with shales, often the micro-organic (animal or vegetable) structures present may characterise a rock as much by their mode of occurrence as by their nature; the uniformity of certain diatomaceous shales, the relationship of vegetal spores to lamination etc., are two instances which may be quoted. Or, quite apart from the organic constituents, the essential structures of these rocks, *i.e.* the degree of parallelism of their component elements, the development of incipient or obvious slaty cleavage, the spherical, elliptical or irregular shape of the coarser (usually quartz) elements, all these may bear comparison from sample to sample, from which identity may be established and correlation rendered possible.

It is not for one moment contended that this line of enquiry *always* leads to precise conclusions or that the method

is infallible; but thin section comparison of core-samples as of outcrop specimens is increasing in favour and this particular bias of what is only, after all, an intensive study of consolidated rocks according to well-established petrological principles, clearly has merits where no other means of correlating such types are available; it should also be remembered that with argillaceous rocks especially, heavy mineral concentrates of sufficient bulk to make their use practicable in subsurface correlation, can only be obtained by treating large quantities of material and this takes time; even then, the results are not always satisfactory.

The prime essential for this technique is a *really thin section*; this observation may seem somewhat trite, but the author has on more than one occasion been presented with problems whose solution was destined to rest on sections containing quartz of vivid interference colours. Admittedly certain sedimentary rocks are extremely difficult to cut very thin without losing important constituents or producing holes; since so much depends on mutual relationship of components, holes at least must be reduced to a minimum. There are, however, ways and means of overcoming the "void" difficulty, as explained in Chapter III. Fortunately skill comes with experience and a good lapidary is seldom mastered, even by a rock-chip measuring less than a quarter of an inch square, a typical "cutting" from the bailer of a cable-tool drill.

The essential petrology of consolidated rocks is dealt with in Chapter X, and is the basis of this particular work. As stated above, differentiation or correlation of samples by means of thin sections rely primarily on composition and structure, both of which receive emphasis in that chapter. Given a good knowledge of the fundamental petrology, it requires relatively little practice to turn one's observations into comparative rather than the more usual descriptive channels; this work is now a recognised part of the routine of almost every subsurface oil-field laboratory known to the author, as it is in all other cases where bore-hole samples have to be determined to elucidate rock succession and structure.

The Study of Accessory Minerals in Igneous Rocks.—The investigation of isolated accessory minerals and heavy mineral assemblages is by no means limited to sedimentary

deposits, as was shown some years ago by R. H. Rastall and W. H. Wilcockson¹ in their work on Lake District granites, later and more exhaustively by A. Brammall and H. F. Harwood in connexion with the Dartmoor granite.² This latter research has specially served as an inspiration to many new workers in this profitable field.

Reference has elsewhere been made to methods of segregating accessory minerals from crushed rocks of whatever character (p. 80). Here we have to note rather their significance and application in modern comprehensive studies of plutonic and associated igneous rocks, an application which parallels closely the technique with which this volume is largely concerned.

In thin section, accessory minerals, save the most prominent and common species such as apatite, zircon and iron-ores, normally escape detection, partly owing to their comparative scarcity with reference to essential rock-forming minerals, partly owing to their small size. Even high magnification, though it may serve to reveal many different individuals, does not offer the fullest facilities of study and diagnosis of these minerals *in thin section* of the rock as a whole, as it does when loose grains or carefully prepared concentrates are studied according to the principles laid down in this volume. Further, in the course of geochemical investigations of such accessory minerals, various physical and chemical tests, apart from those determinations ordinarily made with the petrological microscope, are often necessary to their precise diagnosis and understanding and these obviously cannot be accomplished so long as they are components of consolidated rocks.

The work on the Dartmoor Granite has yielded abundant evidence of the value attaching to an intensive study of such accessory minerals. It has shown the existence of a rich and varied collection of species, many of which were previously not known to occur in that rock; it has stressed and proved conclusively the significance of varietal characters of these minerals and has thus been the direct means of focussing attention on mineral vagaries so often passed by as adventitious or unimportant. The wider investigations, combining both field and laboratory observations, have shown that particular

1, 2 See Bibliography, p. 630, 618.

accessory mineral assemblages may be characteristic of certain "stages" of intrusion or consolidation or of specific developments and modifications of the normal rock, thus materially aiding correlation or differentiation of types. Their potentiality extends also to geochemical data with which petrogenetic problems are intimately bound up. Thus has a new scope of enquiry been instituted, a comprehensive technique established, which neither igneous nor sedimentary petrologist can afford to ignore.

Recognition of progress along these lines is attested by the number of papers which have since appeared dealing with problems and investigations similar to those defined and solved in connexion with the Dartmoor Granite. Among these may be cited the work of M. Chatterjee on the Western Bodmin Moor Granite, of P. K. Ghosh on the eastern part of the Bodmin Moor Granite, of A. W. Groves on the plutonic rocks of the Channel Islands, of D. R. Grantham on the Shap Granite etc., of J. G. C. Leech on the St. Austell Granite, contributions to our knowledge of certain minerals in Scotch granites by W. Mackie and the researches of F. Smithson on the granite and contiguous rocks of Ballycorus district, Dublin.¹

Arising from his work in the Channel Islands, A. W. Groves² claims that isolated plutonic outcrops which possibly may be derived from the same magma may be correlated by means of their accessory minerals, particularly in the case of acid rocks. Thus the technique which has been so useful in the study and correlation of sediments has, according to that author, been extended successfully to igneous rock masses. It is, however, only proper to add that this special application to igneous rocks has been seriously questioned by A. K. Wells,³ who divides the accessory minerals into four groups:—

- (a) normal accessories,
- (b) pneumatolytic accessories,
- (c) contamination accessories,
- (d) secondary accessories.

¹ See Bibliography.

² "The Heavy Minerals of the Plutonic Rocks of the Channel Islands." *Geol. Mag.*, 64, 1927, p. 241, 457; also "The Heavy Mineral Suites and Correlation of the Granites of Northern Brittany, the Channel Islands and Cotentin." *Geol. Mag.*, 67, 1930, p. 218.

³ "The Heavy Mineral Correlation of Intrusive Igneous Rocks." *Geol. Mag.*, 68, 1931, p. 255.

Normal accessories are those developed independently of any special controlling factors such as high flux content, *e.g.* zircon, magnetite, ilmenite, sphene, monazite. Pneumatolytic accessories are produced at a late stage in the cooling of the magma, *e.g.* tourmaline, fluorite, topaz, cassiterite etc. Contamination accessories which infect the magma are those from country rocks, *e.g.* cordierite, andalusite, sillimanite etc. Secondary accessories are those formed as the result of changes of primary minerals, *e.g.* chlorite, serpentine, epidote.

A. K. Wells shows that only the first group, namely normal accessories, can be considered as potential indices of age and correlation; but this implies reliance on such species as zircon, which is common to granites of all ages. He concludes, "The correlation of sedimentary rocks by means of their accessory minerals is itself a difficult matter, and the method has obvious limitations. It does, nevertheless, depend upon a simple and comprehensive principle; a certain suite (determined by the rocks undergoing destruction at the time), will characterize a certain distributive province. No such clear and definite principle has yet been established as the basis of correlation of igneous intrusions by their accessories, and the method must remain inconclusive."

Whatever may be the outcome of any conflict of opinion on this matter, it may be safely assumed that few investigators of igneous rocks according to strictly modern principles will be content to describe their field-types merely from thin section in future and accessory minerals will receive that degree of attention which their importance unquestionably merits. It is equally clear that detrital minerals, considered primarily as accessory constituents of igneous rocks and thus studied "at the source" are made doubly potent in the solution of problems which seek to harmonise igneous and sedimentary activities at different geological epochs. Only by such thorough investigation of parent-rock and contributed sediment, can the full significance of any particular cycle of sedimentation be grasped.

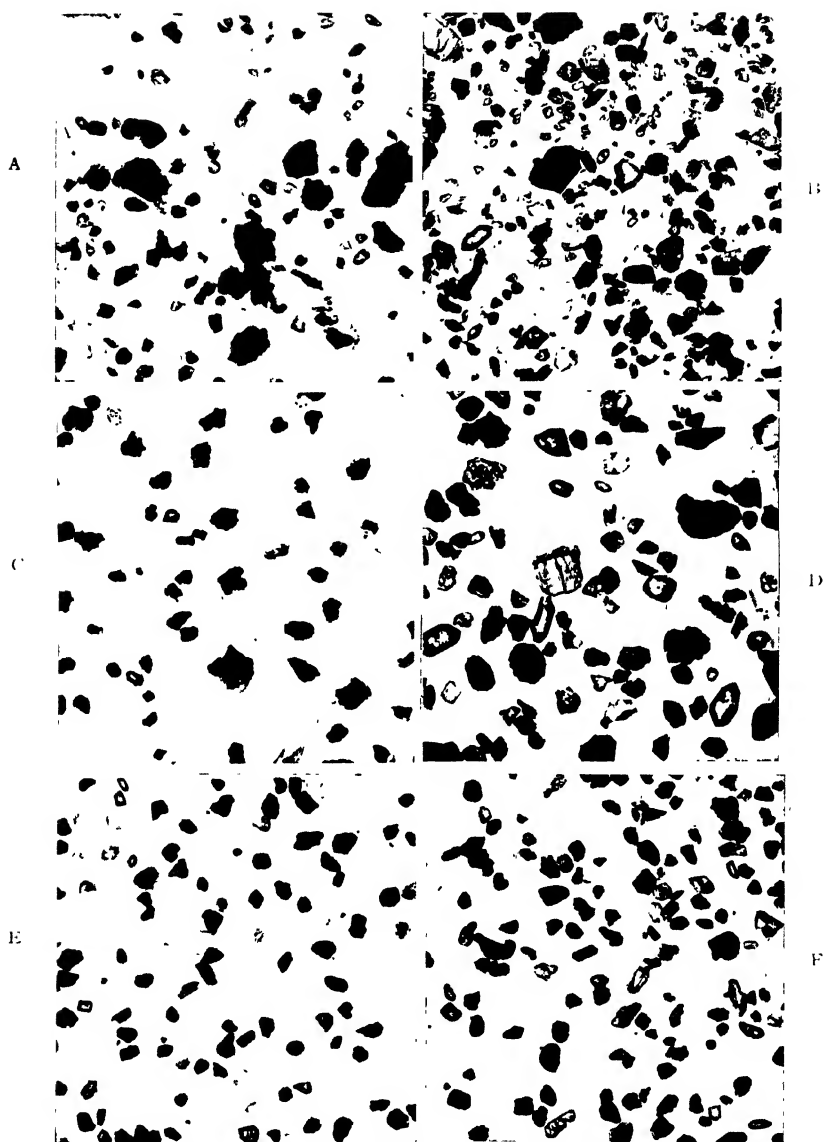
CHAPTER XII.

SOME EXAMPLES OF DIFFERENTIATION AND CORRELATION OF SEDIMENTS BY PETROGRAPHIC METHODS.

Examples of Subsurface Stratigraphical Differentiation and Correlation in the Oilfields of S. California, Texas, Oklahoma, Rumania, Poland—Area (Surface) Correlation illustrated by Cretaceous and Tertiary Rocks of England—Regional work in California—The Correlation of "Outliers."

THE principles and practice of "heavy mineral correlation," as it has come to be known, have been sufficiently discussed in the preceding chapter and are generally appreciated by workers on clastic sediments. There are some, however, who though conversant with the principles, have expressed a desire for a more detailed exposition of actual examples, either carried out on a series of subsurface samples, as under oilfield conditions, or on a series taken from outcropping rocks. There is, in point of fact, no material difference in technique in either case, excepting as already noted in the methods of treatment of the samples; it is true that with outcropping rocks there is often some field-evidence available as a guide to interpretation and conclusion, which evidence may be and frequently is altogether lacking with well-samples.

It is not an easy matter to give a written exposition of the petrographic criteria involved in the differentiation of samples, since so much depends on actual microscopical examination of their residues, on comparison of individual and collective properties of the mineral suites as previously described and on what one may term "intuitive selection," *i.e.* ability to group similar assemblages and to segregate dissimilar assemblages, chiefly a matter of experience. An endeavour is made, however, in the following paragraphs to convey to the reader the essential factors in the work by reference to a few of the many cases now worked out by different petrographers, including the author, in the hope that these examples and some accompany-



A-F. HEAVY MINERAL RESIDUES FROM OIL SANDS IN CALIFORNIA, TEXAS AND ROUMANIA.

- A " Bell Sand," Sante Fe Springs, Calif., U.S.A. [x 25.]
- B " Meyer Sand," Sante Fe Spring, Calif., U.S.A. [x 25.]
- C " Bolsa Zone," Huntington Beach, Calif., U.S.A. [x 25.]
- D. " Ashton Zone," Huntington Beach, Calif., U.S.A. [x 25.]
- E. Oil Sand (Mid. Oligocene) Goose Creek, Texas, U.S.A. [x 25.]
- F Oil Sand (Maëotic), Moreni, Roumania. [x 25.]

ing photomicrographic illustrations may together afford assistance to those engaged for the first time on work of this character. The selection of examples has been chosen to cover most possible cases from subsurface stratigraphy to regional and local field-developments.

CASE I. OIL-SAND DIFFERENTIATION.¹ A series of core- and bit-samples from producing horizons penetrated by certain wells at depths from 3,500 ft. to 4,800 ft. below the surface on the Santa Fe Springs oilfield, Los Angeles basin, Southern California, U.S.A.

*Casual Grouping.*² Into two groups, one characterised by abundant and striking dark green hornblende, the other by epidote, biotite, pyroxene and no hornblende.

Detailed Analysis. The initial grouping into two dissimilar lots is confirmed by the following determinations of the essential constituents:—

Group 1. Residue plentiful, uniform grade, angular:—leucoxene (7),³ green and brown biotite (6), yellow epidote (6), pyroxene and zircon (5), colourless garnet (4), zoisite (3); noteworthy rarity of tourmaline. (Pl. 45 A.)

Group 2. Residue plentiful, mixed grade, subangular:—conspicuous dark green hornblende (8), pale greenish-yellow augite (6), pink garnet (5), green and brown biotite (5), leucoxene (4), epidote and zircon (4), white mica (occasional lepidolite) (3); noteworthy rarity of tourmaline. (Pl. 45 B.)

Group 1, according to the depths recorded on the slides, characterises a zone between 3,500 ft. and 3,850 ft.; the residues of this group are all very similar and no subdivision is possible. (This is the "Bell" or upper oil-zone of the field.)

Group 2 characterises a zone below 3,980 ft. down to 4,800 ft. in some samples investigated; the residues in this group are fundamentally similar, but there is a gradual and progressive change in the relative frequency of hornblende and garnet with depth of sample, deeper samples yielding more garnet than the shallower ones. (This is the famous "Meyer Sand," the main oil-producing horizon of this field.)

Thus the mineral suites characteristic of Groups 1 and 2 respectively are quite different as seen under the microscope, hence samples from the two horizons are easily separated and correlation of each zone from well to well established.

CASE II. OIL-SAND DIFFERENTIATION.⁴ A series of core-samples from two wells close together, from producing horizons of the Huntington Beach oilfield, Los Angeles basin, Southern California, U.S.A. The samples are from depths between 2,780 ft. and 4,850 ft.

¹ Author's analysis.

² This has reference to the first segregations of dissimilar "slides" resulting from the preliminary "run-through" (p. 443).

³ Conventional expression of frequency (p. 457).

⁴ Author's analysis.

Casual Grouping. Into two groups, one characterised by a flood of pyrite, with muscovite, tourmaline and garnet; the other by much less pyrite, much zircon and abundant large, angular pink garnets.

Detailed Analysis. The casual grouping is sustained, but a transitional group between the two main groups is separable as follows:—

Group 1. Abundant residue, somewhat angular; composed chiefly of a flood of angular pyrite, often attached to quartz; muscovite (6), prismatic tourmaline (3), irregular, colourless garnet (5) and zircon (3). (Pl. 45 c.)

Group 2. Abundant residue, subangular; diminishing pyrite, other opaque minerals appearing; pyrite (6), prismatic tourmaline (4), pink garnet, ilmenite and zircon (2).

Group 3. Coarse, angular residue, mixed grade; a little pyrite. Pink garnet (8), zircon (6), tourmaline (4), ilmenite and leucoxene (4), titanite (3), muscovite (2). (Pl. 45 d.)

Group 1, according to the recorded depths of the samples, characterises a zone between 2,780 ft. and 3,240 ft.; this is known as the "Bolsa Zone."

Group 3 characterises a distinctly different and deeper horizon (between 3,500 ft. and 4,850 ft.) known as the "Ashton Zone."

Group 2 characterises a transitional zone between the two in which the diminishing pyrite and gradual enrichment of the residue by other species are observed.

Thus the upper "Bolsa" and lower "Ashton" zones are clearly differentiated and no difficulty is occasioned in separating samples from both, though the extent of the transitional zone might be hard to determine. The lithological evidence of the samples supports the petrographical analysis, those of the "Bolsa" being chiefly sandy shale or mudstone, from which a pyritous and somewhat restricted mineral residue would be expected, the samples from the transitional zone being more arenaceous, while those from the deep horizon are mainly coarse sandstones from which a rich mineral suite might reasonably be anticipated.

CASE III. THE COMPREHENSIVE ANALYSIS OF A PRODUCING OIL-SAND.¹ The chief diagnostic characteristics of one of the Middle Oligocene producing oil-sands at Goose Creek oil-field, Texas, U.S.A. (Average of three samples.)

The samples were obtained from about 2,200 ft. below surface and were submitted to simultaneous micro-organic and petrographic analysis from which the following results were obtained:—

Lithology. Fine, angular sand, somewhat calcareous, with appreciable amount of clay and conspicuous fossil-shell fragments; of the latter, nothing determinate.

*Micropalaeontology.*² Species of *Textulariidae*, *Globigerinidae*, *Rotaliidae* and *Nummulitidae* present; a good foraminiferal assemblage.

Petrography. The essential minerals include quartz, calcite, pyrite and glauconite. Pyrite was removed (p. 75) and the heavy mineral suite

¹ Author's analysis.

² For precise micropalaeontological data see paper by E. R. Applin, A. E. Ellis and H. T. Kniker, "Subsurface Stratigraphy of the Coastal Plain of Texas and Louisiana," *Bull. Amer. Assoc. Pet. Geol.*, 9, 1925, p. 79.

isolated:—ample and characteristic residue, subangular grains; ilmenite and leucoxene (7), tourmaline, garnet, zircon and muscovite (5), kyanite (3), topaz (3), magnetite (3), staurolite (2). (*Pl.* 45 B.)

Thus the nature of the organic assemblage and the characteristic heavy mineral suite render this particular oil-sand clearly identifiable wherever met with and on such evidence correlation of samples from this horizon from well to well is rendered possible.

CASE IV. OILFIELD STRATIGRAPHY: PETROGRAPHICAL DIFFERENTIATION OF "STAGES" AND FORMATIONS. The following example illustrates heavy mineral residue differentiation of recognised palæontological stages and certain principal subdivisions of the Tertiary sequence of the Rumanian Oilfields (Carpathian Foothills). The formations represented are the Pliocene, Miocene and Eocene; the stages represented are the Levantine, Dacian and Mæotic (Pliocene) and the Sarmatian (Upper Miocene), all, among others, critical horizons in this geologically complex region.¹ The series of samples investigated (with the exception of the Eocene) mainly relate to the rocks of the Campina and Moreni districts.

*Petrographic Analysis.*²

Levantine. Abundant and varied mineral suite; angular; mixed grade, 0.1-0.25 mm. Conspicuous feature: abundant angular, colourless garnet.

Assemblage constituted as follows:—colourless garnet (8), brownish-green tourmaline (6), yellow staurolite (5), leucoxene (including ilmenite) (5), rutile and zircon (4), muscovite, blue-green hornblende and epidote (3), kyanite (2), enstatite and blue corundum (sapphire) (1). (*Pl.* 46 A.)

Middle Dacian. Abundant residue, less varied than that of the Levantine; angular; uniform in grade, 0.15-0.2 mm., except for the large brownish-green, prismatic hornblende (0.25-0.3 mm.) the conspicuous feature of the suite.

Assemblage constituted as follows:—prismatic brownish-green hornblende (7), small colourless, angular garnet (5), rutile and tourmaline (4), iron-stained leucoxene (5), muscovite and kyanite (3), staurolite (2). (*Pl.* 46 B.)

Lower Dacian. Abundant residue, somewhat similar to that of the Middle Dacian, but more uniform in grade (0.25-0.3 mm.) and rather more hornblende and garnet relatively to the associated minerals, than in that suite.

Assemblage constituted as follows:—dark green hornblende (8), angular, colourless garnet (3), leucoxene and ilmenite (4), zircon and muscovite (4), tourmaline, rutile and staurolite (3). (*Pl.* 46 C.)

¹ For relevant geological details, reference should be made to two excellent papers, one by G. C. Flower (*Journ. Inst. Petrol. Tech.*, 11, 1925, p. 61), to whom, among others, the author is specially indebted for many of the samples above described; the other by J. Slomnicki and E. Meyer, *Mining Mag.*, 32, 1925, p. 265.

² Author's analysis.

Mæotic. A distinctive and plentiful mineral suite; angular, very mixed in grade, but tending to be small (average 0.1 mm.).

Assemblage constituted as follows:—colourless, small, angular garnet (7), leucoxene (including ilmenite) and green hornblende (5), equi-proportional occurrences of yellow staurolite, brown tourmaline, worn zircon and white mica (4), with accessory rutile (3). (*Pl.* 46 D.)

Sarmatian. A very rich, uniform, fine grade residue (0.1 mm.), quite different in character from the preceding suites. Conspicuous feature is the variety of mica present.

Assemblage constituted as follows:—leucoxene (including ilmenite) (8), garnet (7), muscovite (large flakes, up to 0.35 mm.) (6), green mica (3), greenish-brown biotite (3), tourmaline, epidote, zircon and rutile (5), staurolite (3), glaucophane (2), yellow zircon, kyanite and green hornblende (1). [N.B.—Note impoverishment of hornblende compared with preceding suites.] (*Pl.* 46 E.)

Middle Eocene (Moldavia). Not quite such a prolific yield of heavy minerals as with the other samples, but the suite is again distinctive, the characteristic features being the abundant rutile and zircon and the mixed grade of the residue.

Assemblage constituted as follows:—leucoxene (7), dark brownish-yellow rutile (7), two different types of zircon, large rounded prismatic grains and small fractured grains (together 7), garnet and tourmaline (4), muscovite and staurolite (3), titanite (1). [N.B.—Note absence of kyanite, hornblende and epidote characteristic of some of the above samples and horizons.] (*Pl.* 46 F.)

Thus, not only are the heavy mineral suites yielded by samples from the Pliocene, Miocene and Eocene formations distinctive and accordingly separable, but in the case of the Pliocene, three of the four recognised stages are differentiated (Pontic material not available for study) and further, in that of the Dacian, the very rich oil-bearing horizon, middle and lower subdivisions are recognisable.

CASE V. STRATIGRAPHICAL IDENTITY OF PRODUCING OIL-SAND.¹ Some oil-saturated sands from wells on the Moreni field, Rumania. Determination of the producing horizon. The oil and petroleum residue had to be extracted with chloroform at the outset.

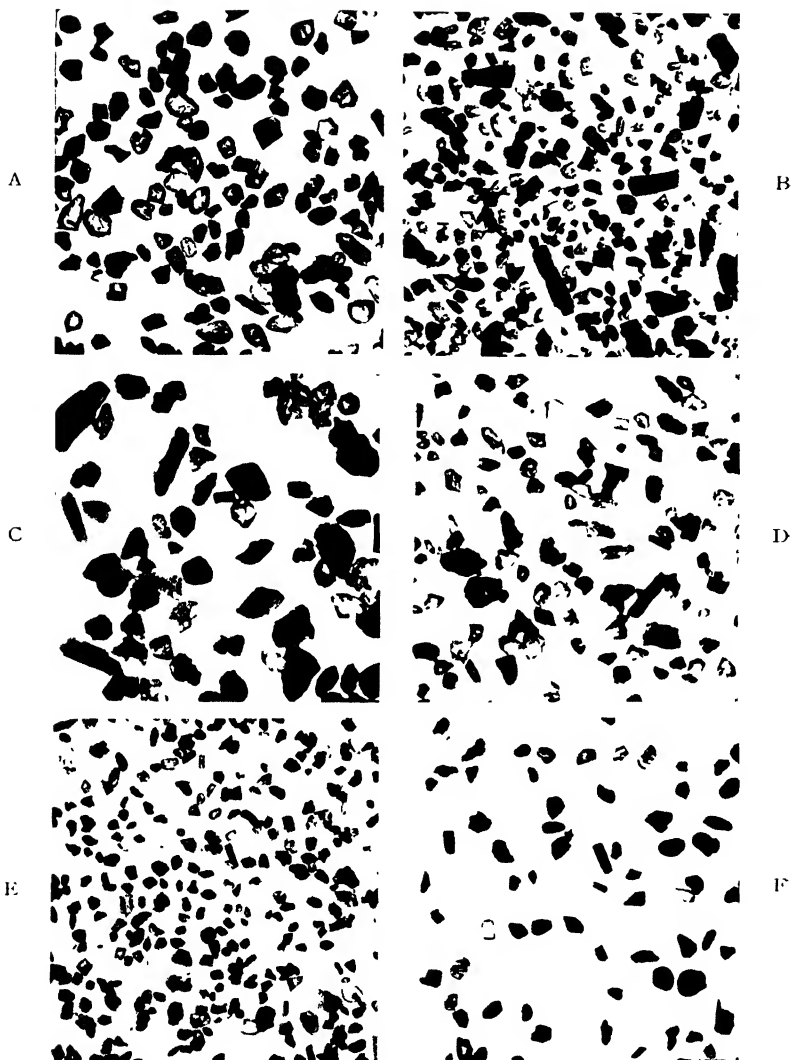
Casual Grouping. All mineral residues similar in this series, no subdivision possible.

Detailed Analysis. The quantity of residue varies somewhat with the samples, but mineralogical composition and physical characters are constant. Suite as follows—leucoxene (including ilmenite) (6), angular colourless garnet (6), zircon (5), yellow staurolite, brown tourmaline and muscovite (4), kyanite (1). (*Pl.* 45 F.)

The minerals tend to be small in grade, about 0.15 mm., and the residue as a whole compares favourably with that obtained from the Mæotic samples described under Case IV above. It lacks the distinctive greenish-brown hornblende characteristic of the Dacian samples, while its general appearance indicates that it bears no relationship to the rocks of that horizon. Hence the Mæotic horizon of these oil-sands is concluded.²

¹ Author's analysis.

² For relevant geological detail, see paper by J. Slomnicki and E. Meyer, *Mining Mag.*, 32, 1925, p. 269.



A-F. HEAVY MINERAL RESIDUES FROM TERTIARY ROCKS, ROUMANIA
[All x 25]

A. "Levantine"
B. "Middle Dacian"
C. "Lower Dacian,"

D. "Maotic,"
E. "Sarmatian"
F. "Middle Eocene,"

CASE VI. FORMATIONS DIFFERENTIATED BY INDEX-MINERALS. H. R. Lovely and F. P. C. Feilman have described an interesting example of petrographic differentiation of two important formations, *viz.* the Wygoda Sandstone (Eocene) and the Jamna Sandstone (Eocene-Cretaceous) of the oilfield region of Boryslaw, Poland.¹ The distinction between the two formations is based in each case on one mineral species, *kyanite* as typical of the Wygoda Sandstone and *epidote* characteristic of the Jamna Sandstone, but absent in the Wygoda; otherwise samples of the deposits contain ilmenite, tourmaline, zircon, garnet, rutile and staurolite common to both and in some instances the respective mineral suites show much morphological resemblance.

CASE VII. CORRELATION OF OIL-SANDS BY EXHAUSTIVE INVESTIGATION OF THE PHYSICAL PROPERTIES OF THE COMPONENT MINERALS. A. C. Trowbridge and M. E. Mortimore have contributed a paper on the correlation of four well-known producing sands, the Wilcox, Hominy, Bartlesville and Elgin, of N.E. Oklahoma, Mid-Continent Oilfield, U.S.A.²

Their thesis is interesting on account of the stress laid on the physical properties (size and shape) rather than on the nature of the mineral constituents of the sands, also for the methods the authors adopt for recording "mechanical, shape and mineral analysis results," *i.e.* by means of graphical representations.

The work is comprehensive and practically amounts to an intensive study of the sediments considered mainly from the lithologic standpoint, though micro-organisms as well as certain accessory heavy minerals are utilised. The graphical representations and charts are supported by photomicrographic illustrations to emphasise the features of dissimilarity between the samples of these sands.

In the case of the four sands and an "unknown" investigated, the data relied on for differentiation and correlation included fossils, degree of angularity and/or rounding of the constituent grains, shale fragments where present, chlorite, muscovite, magnetite, pyrite and pyrite crystals, quartz in greater quantity than 90 per cent., zircon crystals, angular

¹ *Journ. Inst. Petrol. Tech.*, 11, 1925, p. 593.

² *Econ. Geol.*, 20, 1925, p. 409.

zircon, rounded zircon, tourmaline crystals, angular tourmaline, rounded tourmaline; the results may be summarised as follows:—

Wilcox Sand. Grade: well sorted, 55 per cent. to 75 per cent., $\frac{1}{2}$ / $\frac{1}{4}$ mm.; shape: angular, subangular and fairly well rounded grains in equal proportions; no rock-fragments; minerals: muscovite absent, magnetite rare to common, pyrite rare, rounded tourmaline common, more than 90 per cent. quartz; practically unfossiliferous.

Hominy Sand. Grade: fairly well sorted, 40 per cent. to 65 per cent., $\frac{1}{2}$ / $\frac{1}{4}$ mm.; coarser than the Wilcox. Shape: large well-rounded grains; rock-fragments: green shale; minerals: muscovite absent, magnetite variable, crystallised pyrite common, tourmaline angular and well rounded; fossils: limited but recognisable microfauna.

Bartlesville Sand. Grade: not well sorted; shape: angular grains predominate, small percentage of fairly well rounded grains; no rock-fragments; minerals: muscovite rare or common, magnetite rare, tourmaline and zircon rare in crystals, chlorite present; practically unfossiliferous.

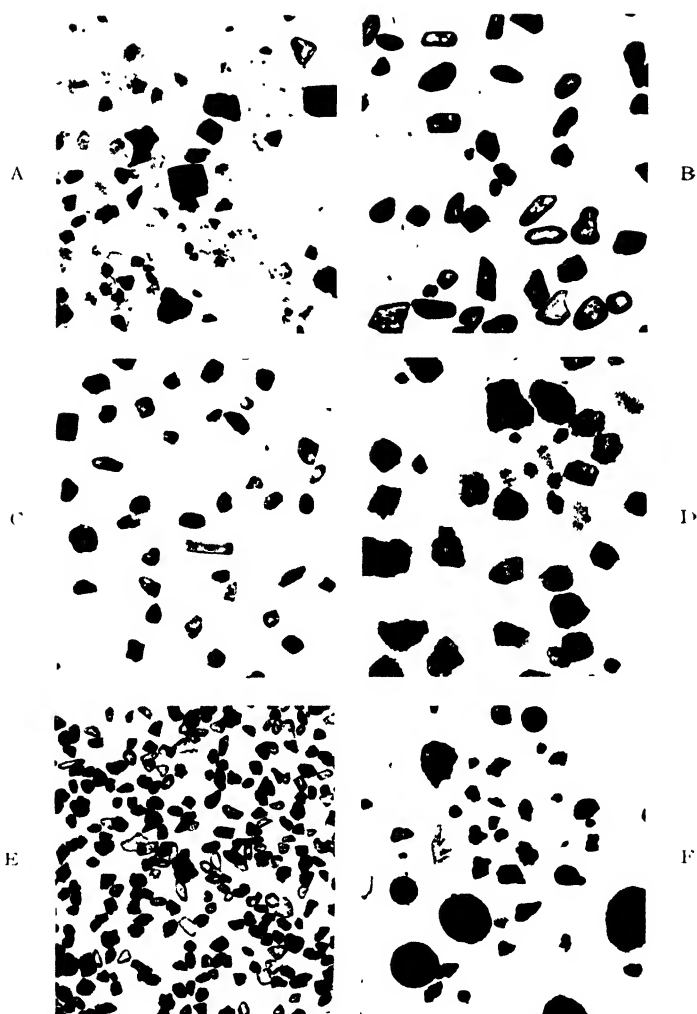
Elgin Sand. Grade: not well sorted; shape: angular grains predominate; no rock-fragments; minerals: zircon and tourmaline common in crystals, angular and subangular grains; unfossiliferous.

Thus it is seen that the identification of accessory heavy minerals is only incidental to the scope of the whole analysis, which depends in the main on the cumulative evidence of mechanical properties; the authors conclude "it is possible to differentiate these four sands by physical characters alone"; they note, however, "certain geographic and geologic limitations to the application of the methods . . ." and "universal application is not claimed."

The comment may be made that this work stresses the significance of constancy or inconstancy of mineralogical properties, including physical criteria in petrographic work. But relying entirely on physical data necessitates quantitative determinations if the results are to have real correlative value and where time is an essential factor, this may be impracticable; in any case, the limitations are probably narrower than when heavy mineral assemblages are used as the governing elements of differentiation, since physical properties of sediments are prone to much more rapid variation than accessory mineral constituents.

CASE VIII. STRATIGRAPHICAL DIFFERENTIATION (FIELD-OUTCROPS). From time to time the author has published accounts of the value of petrographic methods in the geology of the Weald of S.E. England, where the deposits are for the most part exceedingly variable lithologically and where palæontological evidence is often meagre or entirely lacking. Work in the East Grinstead district illustrates this application.¹

¹ H. B. Milner, *Proc. Geol. Assoc.*, 34, 1923, p. 283.



A-F. HEAVY MINERAL RESIDUES, WEALDEN (LOWER CRETACEOUS), S.E. ENGLAND. [All x 25]

- A. Weald Clay (Pyrite, Muscovite, Tourmaline, Zircon, Kyanite etc.), Groombridge, Sussex.
- B. Up. Tunbridge Wells Sand (Leucovene, Zircon, Rutile, Tourmaline etc.), Tunbridge Wells, Kent.
- C. Lr. Tunbridge Wells Sand (Iron Ores, Leucoxene, Tourmaline, Zircon etc.), Ashurstwood, Sussex.
- D. Wadhurst Clay (Pyrite, Mica, Quartz with inclusions etc.), Cullinghurst Wood, E. Sussex.
- E. Ashdown Sand (Iron Ores, Leucoxene, Zircon, Tourmaline, Mica etc.), Fairlight, Sussex.
- F. Fairlight Clay (Sphaerulitic Siderite, Pyrite, Garnet etc.), Fairlight, Sussex.

In this case nearly 200 samples were collected and investigated from outcropping rocks in an area of approximately 36 sq. miles, five different stratigraphical subdivisions being involved and two distinctive lithological developments. The results, for comparative purposes, may be summarised as in the accompanying table (p. 486).

It will be observed that there are significant differences in the amounts of mineral residue extracted from each member of the Lower Cretaceous series represented.

The *Upper Tunbridge Wells Sand* is essentially a zircon-rutile suite of distinctive character; the *Grinstead Clay* has a restricted muscovite-tourmaline-zircon suite, with absence of secondary pyrite (characteristic of the older *Wadhurst Clay*); the *Lower Tunbridge Wells Sand* yields a richer assemblage than the others and zircon is usually subordinate to tourmaline in quantity; *Wadhurst Clay* is characterised by pyrite, mica, chlorite and zircon, while the *Ashdown Sand* gives a zircon-tourmaline-mica suite of fine, uniform grade, the first-mentioned mineral nearly always predominating.

Thus each subdivision is identifiable by reference to its particular mineral assemblage, taking into account not only the minerals themselves and their varying frequencies, but also the physical characteristics of each typical suite. For further petrographic work of a similar nature (involving Wealden rocks), see references cited below, where also, some of the typical residues are further illustrated.¹

CASE IX. STRATIGRAPHICAL DIFFERENTIATION (FIELD-OUTCROPS). S. W. Wooldridge investigated the Bagshot Sands (Eocene) of Essex² and in the course of the work had occasion to draw attention to the striking lithological similarity between them and the older Oldhaven Sands, separated from each other by 400 ft. to 500 ft. of London Clay. He says: "Taken in bulk, the mineralogical contents of the two sands are similar. The differences which appear on closer inspection and which are, moreover, definite and significant, are as follows:—"

In the Oldhaven Beds:

- (i) *Kyanite* larger, better-formed and more abundant.
- (ii) *Rutile*, deep red-brown in angular and rounded grains, larger than similar grains in the Essex Bagshot Sands.

¹ H. B. Milner, *Proc. Geol. Assoc.*, 34, 1923, p. 47; 35, 1924, p. 383; also (with A. J. Bull) 36, 1925, p. 312.

² *Proc. Geol. Assoc.*, 35, 1924, p. 359.

SUMMARY OF PETROGRAPHIC CHARACTERS OF THE WEALDEN BEDS, GRINSTAD AREA, SUSSEX.

LOWER CRETACEOUS						
Horizon	No. of Samples	Lithology	Grade	Percentage "Heavy" Residue (by Wagh)	Character of Minerals	Heavy Mineral Composition (in Order of Frequency)
Upper Tunbridge Wells Sand	20	Sandstone	0.01—0.1 mm.	0.22	Subangular	Leucoxene (8), Zircon (8), Rutile (7), Tourmaline (6), Brookite (4), Anatase (3).
Grinstead Clay Pebble Bed	5	Clay with Sandstone Pebbles	Matrix: <0.01 mm. Pebbles: $\frac{1}{2}$ cm.—2 cm.	—	Pebbles Rounded	Leucoxene, Muscovite, Tourmaline, Rutile, Zircon.
Grinstead Clay	10	Mottled Clay	0.01 & < 0.01 mm.	Approx. 0.02	Irregular	Limonite (after hematite), Muscovite, Tourmaline, Zircon.
Lower Tunbridge Wells Sand : Conglomerate	16	Pebbles in Sandy Matrix	Pebbles : > 2 mm. Matrix : 0.3—0.5 mm.	—	Pebbles Subangular Matrix Angular	Leucoxene (8), Zircon (7), Tourmaline (5), Garnet (5), Rutile (4), Ilmenite (3), Staurolite (2), Hornblende (2), Brookite (2), Monazite (2).
Lower Tunbridge Wells Sand	68	Calcareous Sandstone	0.07—0.25 mm.	0.20	Water-worn Subangular	Leucoxene (8), Tourmaline (7), Zircon (6), Ilmenite (5), Rutile (5), Magnetite (3), Staurolite (3), Hornblende (3), Brookite (2), Anatase (2).
Wadhurst Clay	5	Clay	0.01 & < 0.01 mm.	0.03	Irregular	Pyrite, Zircon, Muscovite.
Ashdown Sand	55	Sandstone Silt	0.05—0.1 mm.	0.01—0.05	Subangular	Muscovite, Leucoxene (8), Zircon (7), Tourmaline (6), Rutile (5), Ilmenite (4), Magnetite (2), Staurolite, Brookite and Anatase sporadic.

- (iii) *Zircon* much less abundant.
- (iv) *Tourmaline*. Green and peach-coloured varieties commoner than in the Bagshot Beds. Also "squat brown prisms which are rare or absent in the latter."
- (v) *Staurolite* is more abundant.
- (vi) *Hornblende* characterised by bluish absorption tints suggesting the presence of the glaucophane molecule.
- (vii) *Garnet* fairly common; rare or absent in newer Eocene.
- (viii) Beds are less micaceous but more glauconitic.

Thus there is plenty of evidence available for distinguishing petrographically between the two formations, quite apart from field-data.

CASE X. STRATIGRAPHICAL DIFFERENTIATION IN CALIFORNIA, U.S.A. F. G. Tickel contributed a paper on "The Correlative Value of the Heavy Minerals," arising from his investigations of some Tertiary formations of part of West Ventura County and the region south of Coalinga, California.¹

He says: "In the region south of Coalinga . . . the Tejon (Eocene) beds can readily be differentiated, microscopically, from the overlying Miocene formations. The Miocene beds contain abundant minerals of the amphibole group, while the Eocene beds contain almost none." In the Fernando (Pliocene) of Ventura River, his work led to the detection of two zones, one characterised by glaucophane and green amphibole, the other by epidote. He concludes: "Study of the heavy minerals constitutes a valuable aid in the correlation of oilfield formations, supplementing and verifying the evidence of the microscopic fossils, or filling the gap where fossils are not found. Mineral grains are not destroyed by the drill; well-samples are just as suitable for study as outcrop samples, and, of course, core-barrel samples offer the best material of all. Much significant information would be obtained by their systematic microscopic study."

CASE XI. A FURTHER CALIFORNIAN EXAMPLE. R. D. Reed has contributed a critical article on the "Role of Heavy Minerals in the Coalinga Tertiary Formations," wherein he discusses the restrictions, advantages and disadvantages of heavy minerals in correlation.² His investigation included typical material from the following horizons:—Avenal (Eocene), Kreyenhagen (Oligocene?), Temblor (Miocene), Santa Margarita (Miocene), Etchegoin (Pliocene) and Tulare (Pliocene).

He states: "Between the Miocene and Pliocene formations of the Coalinga district no persistent differences in heavy mineral content have been discovered. As already suggested, however, any sample of the

¹ *Bull. Amer. Assoc. Petrol. Geol.*, 8, 1924, p. 158.

² *Econ. Geol.*, 19, 1924, p. 730.

Avenal sandstone . . . can readily be distinguished by a mere glance at its heavy minerals, from a sample of any of the Miocene or Pliocene formations. There is no reason to doubt that similar differences may be found elsewhere between otherwise similar formations." "Finally, there is some reason to believe that heavy mineral zones, at least in the California Tertiary formations, are in general thinner than most fossil zones."

While the present author does not agree with certain of the views expressed in this paper, R. D. Reed has clearly established the mineralogical indices of rocks which are not always easily identifiable by other means.

CASE XII. CORRELATION OF OUTLIERS. S. W. Wooldridge and F. Gossling discovered two outliers of Lenham Beds (Pliocene) in Surrey, long thought to be of much earlier Tertiary age.¹ No fossils were found in the beds in question, but their position (relative O.D.) and lithological and petrographical features, are comparable in all respects with similar outlying patches of known Pliocene material on the North Downs.

A comparison of the heavy residues from these beds with established Pliocene deposits (eastern facies) of similar horizon, leaves no room for doubt as to their Lenham character and affinities.

The authors state, "the mineral suite is characterized by the very abundant andalusite, kyanite and staurolite; and by the constant presence of small amounts of monazite, sillimanite and green spinel. A negative character of some significance is the absence of garnet. The suite thus defined agrees closely with that found by Mr. Davies in the more southerly outliers [Lenham etc.], the only difference being due to a slight admixture of Eocene material" . . . "in view of the fact that the beds described occur in such a familiar locality and have been so long overlooked, it has been thought well to present the fullest possible evidence as to the age of the beds, and to emphasize their dissimilarity from the associated Eocene sediments."

The foregoing twelve examples are sufficiently varied as regards geographical and stratigraphical criteria, surface and subsurface occurrence and in technique of investigation, to illustrate the applications of the petrology of sedimentary rocks to stratigraphical problems of all kinds, more especially those involving correlation of doubtful horizons. These examples will, it is hoped, suffice as a guide to similar work anywhere.

¹ *Proc. Geol. Assoc.*, 37, 1926, p. 92.

For further instances of correlation and stratigraphical analysis based on petrographic methods, see references cited.¹

It cannot be too often stressed, however, that competence in diagnosis of detrital minerals and caution in this particular interpretation of their significance are essentials if successful results are to be achieved; proficiency comes with continuous experience with all sorts and conditions of sediments; but the greater that experience, the more cautious the investigator must inevitably become.

- ¹ H. B. Milner, *Quart. Journ. Geol. Soc.*, 78, 1922, p. 348.
P. G. H. Boswell, *Quart. Journ. Geol. Soc.*, 79, 1923, p. 205.
W. F. Fleet, *Geol. Mag.*, 62, 1925, p. 98.
W. F. Fleet, *Proc. Geol. Assoc.*, 38, 1927, p. 1.
R. D. Reed and J. P. Bailey, *Bull. Amer. Assoc. Petrol. Geol.*, 11, 1927, p. 359.
W. G. Shannon, *Geol. Mag.*, 64, 1927, p. 145.
W. G. Shannon, *Proc. Geol. Assoc.*, 39, 1928, p. 137.
F. Smithson, *Proc. Geol. Assoc.*, 42, 1931, p. 125.
G. C. McCartney, *Journ. Sed. Pet.*, 1, 1931, p. 82.
R. Roth, *Journ. Geol.*, 40, 1932, p. 721.
D. R. Derry, *Journ. Sed. Pet.*, 3, 1933, p. 113.
D. R. Derry, *Journ. Sed. Pet.*, 4, 1934, p. 83.

CHAPTER XIII.

THE BEARING OF SEDIMENTARY PETROGRAPHY ON PALÆOGEOGRAPHICAL PROBLEMS.

ALTHOUGH for strictly petrological purposes it may be sufficient simply to effect the qualitative and quantitative examination of a deposit, geologically speaking the investigation is incomplete without carrying the inquiry still further, *viz.* to a consideration of the source or sources of origin of the material and its bearing on the palæogeography of the area at the time of deposition. The perusal of this more philosophical aspect of the science is not merely academic; indeed, one might almost say that without such an inquiry all petrographic work must lose both in precision and value: it will certainly lack vitality. As an aid to problems of correlation on the lines discussed in Chapter XI, such research is of fundamental importance.

Tracing the source of constituent particles of a deposit is often by no means a straightforward matter, especially where the locale of a distributive province capable of furnishing the material is obscure or where, owing to widespread erosion, no direct evidence of such a province exists. The problems to be faced are, from their very nature, some of the most complex and absorbing that a geologist has to solve and each case must perforce be dealt with on its own merits. Accordingly, we cannot presume to do more than indicate here certain broad factors to be taken into account in all considerations of this character, leaving it to the initiative and ability of the investigator to evolve the more detailed plan likely to lead to the most reasonable conclusions in the particular case with which he is concerned.

The mineralogical analysis of a sediment will show a certain suite of detrital grains which may or may not be suggestive of the source of origin, either individually or collectively.

Generally speaking, there is seldom an instance where the petrographer fails to gain some clue, however small, to the source of some at least of the species represented. In the descriptions of the detrital minerals given in Chapter IX, possible sources of origin of the several species are included to enable an initial estimate to be made; this information, however, only applies to individual grains. Paragenesis is just as important a factor in detrital sediments as in igneous or metamorphic rocks and more often than not indication of the source of origin of the deposits comes from association of species noted rather than from particular minerals.

The association of sillimanite, kyanite, andalusite and garnet or again, a garnet-staurolite-kyanite suite, are both suggestive of derivation from a definite thermo-metamorphic province, just as a titanite, apatite and zircon assemblage (if marked) is indicative of acid or intermediate plutonic rock-types as possible sources of supply. The characteristic association of rhombic and monoclinic pyroxenes, often with ceylonite and possibly a chlorite group mineral in addition, points to derivation from basic or ultrabasic rock-types, while the prevalence of cassiterite, topaz, white mica and rare-earth minerals in certain sands may be equally suggestive of their primary environment. On the other hand, a predominance of the more stable minerals such as zircon, tourmaline, rutile and iron-ores, probably to the total exclusion of such other species as are mentioned above, implies derivation from pre-existing sediments and in such cases location of the ultimate source of origin may be rendered considerably more difficult.

Knowledge of likely mineral associations is also helpful in diagnosis. Paragenetic species not only suggest provenance, but imply certain "index" minerals anticipatory of related detritals for which the assemblage may be profitably searched. For instance, where diagnosis of a particular mineral proves difficult and a decision between two or more possibilities has to be made, the claim of the more likely species, deduced from the presence of "indices," often leads to positive identification. Examples of "index" minerals and the suites thus implied may be given :—

Olivine, magnetite, chromite, picotite, antigorite or chrysotile, ceylonite, rhombic and monoclinic pyroxenes.

Cassiterite, tourmaline, topaz, fluorite, apatite, muscovite, hypersthene.
Corundum, purple quartz, topaz, garnet, spinel, monazite, titanite,
 (?) beryl, often with members of the sillimanite suite (below).
Sillimanite, kyanite, andalusite, chiastolite, staurolite, topaz, monazite,
 tourmaline, garnet, cordierite.
Diopside, rhombic and monoclinic pyroxenes, amphiboles, olivine.
Epidote, chlorite group, zoisite, garnet, vesuvianite.
Axinite, tourmaline, hornblende, biotite, titanite, epidote, pyroxene.
Chloritoid, muscovite, biotite, tourmaline, titanite, garnet and quartz
 with abnormal interference colours (strain), pyrite, chlorite group
 minerals, graphite, corundum, spinel, rutile.

The "index" minerals are *italicised* in the above lists, but it is obvious that other species in the suites may individually or collectively assume equal importance. Once a particular mineral association is established and its relationship to a definite source of origin inferred, confirmation of such provenance should be sought by appealing to significant varietal characters of the index-species. This, however, implies detailed knowledge of the parent-rocks themselves, quite apart from the sediments involved.

Investigations of provenance must take into account not only heavy mineral evidence but also that arising from a study of the coarser constituents, *i.e.* boulders, pebbles and rock-fragments of macroscopic size. Many examples of the significance of these components occur throughout the literature; we may cite A. Gilligan's investigations of the pebbles of the Millstone Grit of Yorkshire;¹ T. G. Bonney's work on the Bunter Pebble Beds of the Midlands² and the author's study of Wealden deposits of S.E. England, in which conglomerates developed at certain horizons contain pebbles of undoubted Jurassic origin, thus confirming other evidence as to the essentially sedimentary provenance of these rocks.³

In another direction, investigation of the nature of inclusions in minerals, especially in quartz, frequently repays detailed study; this follows along the lines laid down by W. Mackie in the course of his work on various Scottish rocks;⁴ it is emphasised by A. Gilligan in his researches on the Millstone Grit referred to above, while significance of varietal features of and inclusions in certain prominent Dartmoor

¹ *Quart. Journ. Geol. Soc.*, 75, 1919, p. 253.

² *Quart. Journ. Geol. Soc.*, 56, 1900, p. 287.

³ *Proc. Geol. Assoc.*, 34, 1923, p. 297.

⁴ *Trans. Edinburgh Geol. Soc.*, 7, 1896, p. 148.

minerals has been discussed by A. Brammall in his masterly contribution to the subject of provenance.¹ Writing of the typical Dartmoor detrital assemblage, that author summarises evidence of "Dartmoor provenance" in terms so lucid as to rank them as first principles of far wider application. He says, "Individually the species enumerated . . . do no more than suggest the possibility of a Dartmoor provenance, but possibility might be strengthened to probability by coincidences based on (a) relative abundance, (b) varietal features, and (c) nature of inclusions. Whether probability could itself be strengthened to carry conviction would depend on the number of such coincidences. For example:—Zoned zircons alone are of little value as evidence of Dartmoor provenance. Their evidential value rises by virtue of inherent features (abundance, size, nature of inclusions etc.), and of associations: if they are associated with clear zircons subordinate in amount and showing certain peculiarities, their value is enhanced, and this value rises progressively by association with octahedrite, tabular anatase, monazite, brookite, mangiferous garnet etc., in varietal agreement with known Dartmoor species. Scrutiny of material along these lines implies the need for an exhaustive examination of material"²

The importance of these observations is realised by all workers on sedimentary deposits to which the Dartmoor Granite and its associated rocks have been laid under contribution, as was shown by A. W. Groves in connexion with the distribution of its detritus in S. England.³ But the example is of universal significance and the principles implied underlie every investigation into the source of origin of sedimentary rocks.

It frequently happens that a particular mineral will, in its form, colour or other specific character, betray its source of origin by strong resemblance to the same species known to occur in older rocks; this is especially the case with younger sediments which have in part been derived from the breaking up of pre-existing detritus. In this way a flood of light may

¹ *Proc. Geol. Assoc.*, 39, 1928, p. 27

² *Ibid.*, p. 47.

³ *Quart. Journ. Geol. Soc.*, 87, 1931, p. 62.

be thrown not only on the direction and mode of transport, but also on physiographical conditions prevalent at the time of deposition. Thus, staurolite occurring in the Bunter Pebble Beds of S.W. England has been traced to the Armorican massif (or its more northerly extension in Triassic times): hence is deduced the prevalent flow of sediment-bearing currents from the south.¹

The author's work on the Pliocene deposits of Cornwall showed that staurolite occurring in these has had the same derivation, while the presence of Lower Cretaceous types of kyanite in the most northerly localities has suggested the flow of sediment-bearing rivers from the north-east, *i.e.* from the region in which, in Pliocene times, the main mass of Cretaceous rocks was extant.² Again, in view of W. Mackie's researches on the accessory minerals of Scottish granites (in which he proved the occurrence of monazite in 43 out of 52 examples examined³), the presence of this species in the Millstone Grit of Yorkshire joined to other evidence reinforces the argument in favour of the contention that that deposit had a northerly derivation.⁴

Later work on the source of purple zircon in Scottish sedimentary rocks furnished yet another instance of the significance of a particular variety of a mineral in connexion with problems of their origin.⁵ In this case the provenance is the Lewisian Gneiss. By the same indication it has been shown that the Moine Series is older than the Torridonian and that the latter rocks owe their origin partly to the Archæan Gneisses and partly to the Moine Schists. In view of the fact that purple zircon is also widespread in many other sedimentary rocks in this country, being met with, for instance, in Eocene deposits as far south as Dorset, Devonshire and Cornwall, P. G. H. Boswell's contribution to the distribution of this variety is both interesting and suggestive.⁶ In short, once the ultimate geological source is established of a mineral whose specific properties proclaim it an adequate indicator, it becomes *per se*, an invaluable

¹ H. H. Thomas, *Quart. Journ. Geol. Soc.*, 58, 1902, p. 630.

² *Quart. Journ. Geol. Soc.*, 78, 1922, p. 348.

³ In A. Gilligan, *Quart. Journ. Geol. Soc.*, 75, 1919, p. 271.

⁴ A. Gilligan, *op. cit.*

⁵ W. Mackie, *Trans. Edinburgh Geol. Soc.*, 11, 1923, p. 200.

⁶ *Mineral. Mag.*, 21, 1927, p. 310.

guide not only in "placing" the distributive province, but also in reconstruction of the salient events with which the particular sediment or sediments have been concerned.

In working out problems of this nature, therefore, it is advisable firstly to note the possible types of rocks from which each mineral species may have been derived and secondly to investigate the presence (or absence) of such types within a likely region capable of furnishing the material. In this way palæogeographical questions arise collaterally and the unravelling of the geological record within the limits of the periods represented by both parent-rock and sedimentary deposit constitutes the crux of the whole matter.

Palæogeographical restoration, to be complete and accurate, necessitates detailed knowledge of regional stratigraphy and also the absence of imperfections in the geological record. The former may be acquired by the geologist as a result of detailed work—in fact its realisation is a *sine qua non* to the successful prosecution of all petrographic work. The latter is largely a matter of chance and naturally varies in different districts. Obviously the more faithfully the history of past geological events is chronicled by the rocks, the more complete is the stratigraphical record and solutions to problems of geographical reconstruction are facilitated accordingly. If, in this connexion, we compare south-east with south-west England, it is at once apparent that palæogeographical investigations in the former, where there are few gaps within the limiting series as developed, are much more straightforward than in the latter region, where no evidence whatever is preserved of the trend of events between late Palæozoic and early Tertiary times.

Again, the evidence of organic remains (where these are preserved) must obviously play a fundamental part in inquiries of this nature; only where palæontological investigations are followed hand-in-hand with petrographical analysis can we expect to gain the fullest knowledge, enabling each step in the process of reconstruction to be made with a reasonable degree of accuracy.

The bearing of certain detrital minerals on questions concerning climatic conditions prevalent at the epoch of deposition has received a good deal of attention from various observers.

Under certain conditions the evidence afforded is convincing, especially in the case of felspar grains, but frequently it must be admitted that the indications are inconclusive. As early as 1886 J. W. Judd described the freshness of the felspar grains of the Nile deposits as indicative of mechanical disintegration and desert conditions, *i.e.* tropical heat by day and rapid cooling by radiation at night.¹ H. B. Medlicott and W. T. Blanford,² of the Indian Geological Survey, have directed attention to differentiation of altered and unaltered felspar grains, the latter as indicative of mechanical attrition, the former of chemical weathering; in this way felspar grains present in the Siwalik deposits and also in the Indo-Gangetic alluvium, are ascribed to the breaking down of the parent-rocks by ice and frost, since they are remarkably fresh and unaltered.

W. Mackie's paper "Felspars in Sedimentary Rocks as Indicators of Climate,"³ is another instance of detailed research in the differentiation of fresh and altered felspar grains as criteria of mode of attrition, hence of prevalent climatic conditions. Where alteration is very marked, the inference to be drawn is that moist and humid conditions prevailed, tending to promote chemical decay; where freshness of felspar is the marked feature, mechanical attrition under arid or glacial conditions is suggested and in such cases a decision must be made between the one or the other by general stratigraphical and lithological evidence; the marked angularity of grain characteristic of glacial deposits, usually contrasts in a striking manner with the strong tendency to rounding exhibited by æolian detritus.

The conditions attendant on deposition of the Millstone Grit indicate a prevalent monsoon type of climate, by which heavy rains, capable of feeding large rivers, were maintained; hence weathering of the material was preponderantly mechanical, as evinced also by the character of the grains and particularly by the "exceeding freshness of the felspars."⁴

The more detailed study of detrital minerals has shown that not only felspar, but also minerals like staurolite, andalusite and kyanite may be indirectly indicative of climatic conditions,

¹ *Proc. Roy. Soc.*, 39, 1886, p. 215, 217.

² "Manual of the Geology of India," 2nd ed. (Trübner, London), 1893, p. 201.

³ *Trans. Edinburgh Geol. Soc.*, 1898, p. 443.

⁴ A. Gilligan, *op. cit.*

partly from observations of their degree of alteration and partly from considerations as to their ultimate origin. In the Pliocene deposits of Cornwall the staurolite grains preserve a subangularity entirely consistent with marine transport; their source of origin from the south-west is suggestive of prevalent currents from that direction, thus reflecting present-day conditions. Confirmatory evidence of this is to be found in the location of the Pliocene outlier at St. Agnes on the leeward side of St. Agnes Beacon (N.E.), and by comparison with prevailing climatic conditions of Cornwall to-day, where heavy rains frequently accompany south-west winds, we may infer, with a reasonable degree of accuracy, somewhat similar conditions operative in early Pliocene times.¹

The evidence afforded by andalusite is rather more obscure, but a study of the mineral shows that there are two distinct types of weathering, one characteristic of the species derived from contact metamorphic rocks, the other characteristic of grains derived from andalusite-bearing granites. In the former case the degree of alteration is usually far more advanced than in the latter instance: sericite, kaolinite and possibly chloritic matter may be so prevalent as to cloud the grains entirely, particularly under climatic conditions favourable to intensive chemical weathering. This will apply, of course, to a certain extent to grains derived from granitic rocks under similar conditions, but it is a noteworthy fact that, where this source of the mineral is determined, its freshness and form are clearly indicative of mechanical disintegration, generally under rather frigid climatic conditions.

The investigation of the mineralogical constitution of sedimentary rocks has now proceeded far enough for the geochemical significance of commonly occurring detrital and authigenic species to be appreciated and discussed with a fair degree of accuracy. The cumulative evidence of the study of sediments of all types and geological ages impresses us with certain well-marked tendencies whereby definite minerals or groups of minerals become criteria of environmental conditions. This does not imply merely a potentiality of these minerals to indicate provenance or peculiar climatic conditions, but rather

¹ H. B. Milner, *op. cit.*

their role as indices of the varying natural influences, collectively determining the natural history and ultimate geological character of sedimentary formations.

Any special meaning attaching to the presence of some particular mineral or suite of minerals may be directly interpreted from them or may only be suggested when there are other terms of reference; thus a series of altered microcline grains may be accepted as evidence of a humid environment of sedimentation; or glauconite may in a majority of cases be sufficient proof of a marine environment; but the reason or precise significance of the occurrence of apatite, barite or dolomite in a sediment may not be apparent until full lithological and petrographical data are known.

The presence, as also the absence, of primary rock-forming minerals in sediments *ipso facto* raises questions of relative chemical and physical stability; the survival of certain species under one set of conditions and their destruction under another, are alike provocative of further investigation leading to valuable stratigraphical conclusions; authigenic minerals may not only imply specific geochemical reactions, but they may also directly signify by the nature and achievement of such reactions, environmental conditions; in short, there is a wealth of natural history to be learnt from an intelligent interpretation of sedimentary rock-minerals and it is the purpose of the remaining paragraphs of this chapter briefly to summarise significant data in this connexion. Apart from focussing attention on a theoretical aspect of the petrology of sediments, it is hoped that this contribution will, by creating yet another perspective, serve to stress once more the true aim and scope of all intensive petrographical research.

Preliminary to annotation of the individual minerals and varieties dealt with in this book, it is convenient to summarise in tabular form their general tendencies in sedimentary deposits as regards mode of occurrence, stability and comparative frequency.

“ Under normal conditions the number of different mineral species occurring in sediments is not great; possibly twenty-five is a fair average for detrital deposits, especially of younger geological age. Older geological deposits (pre-Permian) tend to have a much more restricted composition. . . . Allow-

Mineral	Occ.	Stab.	Freq.	Mineral	Occ.	Stab.	Freq.
Actinolite	D	s	l	Hercynite	D	s	r
Ægirine	D	s	r	Hiddenite	D	S	vr
Agate	D & A	S	l	Hornblende	D	S	vr
Albite	D & A	s	l	Humite	D	S	vr
Allanite	D	S	r	Hypersthene	D	S	r
Allophane	A	S	l	Iddingsite	D	S	r
Almandine	D	S	c	Ilmenite	D	S	c
Analcite	D & A	s	r	Jasper	D & A	S	c
Anatase	D & A	S	c	Kaolinite	D	S	c
Andalusite	D	s	l	Kunzite	D	S	vr
Andesine	D	s	l	Kyanite	A	S	vr
Andradite	D	S	vr	Labradorite	D	s	l
Anhydrite	A	S	l	Lawsonite	A	S	l
Ankerite	D & A	S	c	Lepidolite	D	S	vr
Anorthite	D	U	vr	Lepidomelane	D	S	vr
Anorthoclase	D	s	l	Leucoxene	A & D	S	c
Antigorite	D & A	s	r	Limonite	A	S	c
Apatite	D	U	r	Magnetite	D & A	S	l
Aragonite	D & A	s	c	Magnetite	D & A	S	l
Artvedsonite	D	s	r	Marcasite	A	S	l
Augite	D	s	l	Melanite	D	s	r
Axinite	D	s	vr	Microcline	D	S	vr
Barite	A	s	l	Monazite	D	S	vr
Barkevicite	D	s	l	Montmorillonite	D & A	S	c
Basaltine	D	S	l	Muscovite	D & A	S	c
Bastite	D	s	l	Nephrite	D & A	s	r
Beidellite	A	s	c	Nontronite	D & A	S	l
Benitoite	D	s	vr	Oligoclase	D	S	c
Biotite	D	s	c	Olivine	D	U	r
Bronzite	D	s	l	Omphacite	D & A	S	r
Brookite	A & D	S	r	Opal	A	S	c
Bytownite	D	U	vr	Orthoclase	D	S	c
Calcite	D & A	S	c	Orthelite	D	U	vr
Cassiterite	D	S	l	Penninite	D & A	S	vr
Celestine	A	S	l	Periclase	D & A	U	vr
Ceylonite	D	S	r	Phlogopite	D	S	vr
Chalcedony	D & A	S	c	Picotite	D	S	vr
Chert	D & A	S	c	Piedmontite	D	S	vr
Chiasolite	D	s	l	Psilomelane	A	S	l
Chloritoid	D & ? A	s	r	Pyrite	A	s	c
Chromite	D	s	vr	Pyrolusite	A	s	l
Chrysotile	D	s	l	Pyrope	D	S	l
Clinocllore	D & A	s	c	Pyrophyllite	D & A	S	r
Clinzoisite	D	s	r	Pyrrhotite	A	U	l
Collophane	D	S	l	Quartz	D & A	S	c
Cordierite	D	U	r	Riebeckite	D	U	r
Corundum	D	S	r	Ruby	D	S	c
Crossite	D	S	vr	Rutile	D & A	S	l
Cymatolite	A	s	r	Sanidine	D	S	l
Delessite	D	s	r	Sapphure	D	S	l
Diallage	D	s	l	Selenite	A	s	l
Diamond	D	vr	vr	Siderite	A	S	l
Diaspore	D & A	s	l	Sillimanite	D	S	r
Dickite	D	s	r	Spes-artite	D	S	vr
Diopside	D	S	l	Sphalerite	D & A	S	vr
Dolomite	A & D	S	l	Spinel	D	S	r
Dumortierite	D	S	vr	Spodumene	D	S	vr
Enigmatite	D	s	vr	Staurolite	D	S	c
Enstatite	D	S	r	Steatite	D & A	s	l
Epidote	D & A	S	c	Strontianite	D & A	s	l
Fayalite	D	S	vr	Sulphur	A	U	l
Flint	D & A	S	c	Thulite	D	S	vr
Fluorite	D & A	S	r	Titanite	D & A	S	r
Fuchsite	D	s	l	Topaz	D	S	c
Galena	D & A	S	l	Tourmaline	D	S	c
Gastaldite	D	s	vr	Tremolite	D	S	vr
Gibbsite	D & A	s	l	Uvarovite	D	vr	vr
Glaucosite	D & A	s	c	Vesuvianite	D	S	vr
Glaucophane	D	s	r	Viluite	D	S	vr
Goethite	D & A	s	l	Wolframite	D	S	l
Graphite	D & A	S	r	Wollastonite	D	S	r
Grossularite	D	s	r	Xenotime	D	S	vr
Gypsum	A	S	l	Zircon	D	S	c
Halloysite	D & A	s	c	Zoisite	D	S	r
Hematite	D & A	s	c				

N.B.—In the above table the tendencies are denoted as follows:—occurrence (*Occ.*) by D=detrital, A=authigenic and D & A=both; stability (*Stab.*) (chemical) by S=stable, s=moderately stable and U=unstable; comparative frequency of occurrence (*Freq.*) by c=common, l=local, r=rare and vr=very rare.

ing for certain environments where special types of igneous or metamorphic rocks constitute the source of supply of material, the list of possibilities is much larger, though the number of actually occurring species may be comparatively small. Under still more local conditions, for instance, where rarer types of metamorphic rocks or even metalliferous ores contribute material it is obvious that any stable mineral may occur in the derived sediment if initially present in such parent rock-types."¹

The following geochemical notes are intended to be suggestive, not dogmatic:—

Actinolite. Fails to survive prolonged transport; presence usually suggests proximity of parent-rock (metamorphic); incipient alteration to minerals of the chlorite group indicates hydrous environment; to calcite, lime infiltration or influence.

Ægirine. Indicative of alkaline igneous rock province, especially syenite (e.g. *elæolite* syenite) and frequently associated with feldspathoid minerals (e.g. *leucite*). Tends to alter to *analcite*. Unstable when detrital and not to be anticipated in sediments of geological age.

Agate. See under *Chalcedony*.

Albite. May be classed as a stress mineral in metamorphic rocks where shearing stress is in evidence, hence to be anticipated in sediments where such material is laid under contribution. As with oligoclase and andesine is much commoner in sediments than the other members of the plagioclase feldspar group. Albite is not entirely confined to igneous rocks, having been found indigenous to certain marine calcareous muds and dolomites (R. L. Daly, *Proc. Nat. Acad. Sci.*, 3, 1917, p. 659). Liable to alteration in aqueous environment, accentuated in presence of CO₂ or acids, less commonly in contact with alkaline solutions. End products may be sericitic mica and kaolinite or simply kaolinite and quartz.

Allanite (Orthite). Frequently paragenetic with epidote, but liable to alteration to rare-earth carbonates (e.g. *cerium*). Often associated with biotite, in which it occurs as inclusions and thus released on disintegration of that mineral.

Allophane. A product of hydrous alteration closely allied to kaolinite, halloysite, montmorillonite and associated "clay" minerals. Generally authigenic.

Almandite. Frequently by its form an indication of the intensity of æolian corrosion, aqueous abrasion etc. Under certain conditions (? mechanical) it is singularly unstable and is "lost" in deposits where it might be anticipated to occur in quantity. Chemical alteration in sediments (rarely seen) tends to chloritic matter: some of the isotropic green grains observed in porous sandstones may represent this change; non-survival may be due to chloritisation following mechanical disintegration, but further observations are necessary.

Analcite. Generally a secondary mineral formed in association with other zeolites. It may replace nepheline or sodalite. Zeolitisation often proceeds from hydration of feldspar, in this case from soda-bearing plagioclase.

¹ H. B. Milner, *Mining Mag.*, 1923, p. 80.

class or orthoclase containing Na. Analcite may be formed by degeneration of soda-bearing ferromagnesian silicates, *e.g.* ægirine. In certain cases it has been proved to be a primary constituent of deep-seated rocks formed under pressure. Its occurrence in sediments must always be a matter of more than usual interest, having regard to its origin and general instability when released from parent rock.

Anatase. See under *Ilmenite*.

Andalusite. Degenerates with time; may be replaced by kaolinite in "sealed" environments; alteration to mica denotes hydration and is facilitated by high porosity of sediment. When plentiful a possible indicator of geologically young deposits; universally widespread in Pliocene sediments, especially the most porous arenaceous developments; has been recorded from Old Red Sandstone (W. Mackie). An anti-stress mineral.

Andesine. A member of the plagioclase feldspar group characterising particularly intermediate igneous rocks, *e.g.* diorite, andesite. Records indicate that it is less common in sediments than either albite or oligoclase.

Andradite. A conspicuous member of the garnet group and probably often overlooked in sediments unless carefully searched. Indicative of derivation from feldspathoid-bearing igneous rocks, *e.g.* nepheline syenite; alternatively, it may suggest contact-altered parent rocks especially if wollastonite is present; more rarely, when found with diopside, augite or rarer forms of pyroxene, it suggests a volcanic provenance.

Anhydrite. Originates in the majority of cases by precipitation from saline solution, one of the earliest products to crystallise out with the process of gradual desiccation of land-locked waters. Commonly associated with rock-salt, gypsum and other sulphates. Is readily changed into gypsum by hydration, but the reverse reaction is also possible and has been observed. It may also form at the expense of limestone. In thick deposits or massive state is inferential of lacustrine, lagoonal or land-locked sea environment. In the presence of excess of organic matter, anhydrite may be reduced and deprived of its sulphur or, put in another way, access of methane to anhydrite (or gypsum) produces calcium carbonate, sulphuretted hydrogen and water; the reaction is probably reversible and this accounts for the diversity of conditions under which anhydrite is found. This mineral should always be studied in its relationship to associated salts and other rock-types.

Ankerite. Affiliates dolomite and siderite and is developed under similar conditions to the former, though implying co-existence of iron-bearing solutions. As an authigenic mineral ankerite is often found in association with coal, but generally its habitat is limestone, in which it is often accompanied by pyrite and sometimes authigenic albite.

Anorthite. The lime-bearing plagioclase feldspar derived essentially from ultrabasic rocks, less commonly from contact-altered limestone. Anorthite tends to alter rapidly, usually to sericitic mica, kaolinite, one or other of the zeolites, zoisite or calcite and it therefore fails to survive transference to sediments except under exceptionally localised conditions; such alteration is chiefly brought about under hydrous conditions, especially in the case of calcite where percolating waters charged with CO₂ have access.

Anorthoclase. Intermediate between albite and microcline in composition and partaking of the same degeneration characteristics as those minerals (*q.v.*). Its presence in sediments implies derivation in part from volcanic rocks of an alkaline petrographic province. Frequently associated with sanidine (with which it may be intergrown) which, if found, provides confirmatory evidence of provenance of the sediment involved. Its

occurrence in certain Cretaceous Fuller's earths of Britain is significant (see p. 242).

Antigorite. Essentially an alteration product characterising serpentine rock, developed from such minerals as olivine, enstatite, hornblende, diopside or other magnesian minerals in environments where relaxation of basic and ultrabasic rocks is brought about by hydrous or hydrothermal conditions. Never a primary species. Persistence in sediments determined by proximity to relevant source of supply: not to be anticipated in deposits of geological age or where long-distance transport is implied.

Apatite. Survives in argillaceous (impervious) rather than arenaceous (porous) rocks, or in "sealed" sediments, e.g. loamy Thanet Sand protected by cover of Chalky Boulder Clay (P. G. H. Boswell); destroyed in lime environments by solvent action of carbonic acid generated by percolating water; present usually in silt, clay, shale or red marl, products of continental, lacustrine, fluvial, rarely brackish marine environments. Degenerates under marine conditions forming secondary phosphates aided by organic selection (see *Glaucinite*). Has been noted in Old Red Sandstone (P. G. H. Boswell).

Aragonite. Given the presence of magnesium sulphate in solution and a temperature exceeding 29°C, any carbonate which may be precipitated will be aragonite, not calcite. In this way much of the aragonite is formed which occurs in association with limestone and saline deposits, though another source is the shells of certain organisms (p. 393). Aragonite indicates, *ceteris paribus*, climatic control and a warm sea. The presence of sodium or ammonium carbonate in sea-water favours its precipitation; under conditions in which organic decay is prevalent, the ammonium compounds would tend to be formed, especially in warm environments, thus aiding the deposition of aragonite. This mineral changes easily to calcite, but the reverse process has not been observed authoritatively.

Arfvedsonite. Identification in sediments of this amphibole implies derivation from soda-bearing igneous rocks, e.g. nepheline syenite and related pegmatites. It is not, when released, particularly stable, however and may be wholly or partially replaced by siderite or limonite.

Augite. If in quantity and fresh, indicates either proximity to parent-rock or preservation in anhydrous environment; degenerates with time, hence met with normally in youthful deposits. An anti-stress mineral.

Axinite. Beyond suggestive of pneumatolytic provenance, usually the product of contact-alteration of basic (lime-bearing) igneous rocks, this mineral is of no special significance.

Barite. Normally authigenic, but may be locally derived; cementing medium of porous, arenaceous rocks suggesting percolating carbonate- and sulphate-charged waters; or reaction between bicarbonate (infiltrating) solution and pyrite under oxidising conditions; initially liberated (as barium oxide?) by decomposition of barium-bearing feldspar and mica, especially by subaerial weathering of acid igneous rocks and as an authigenic mineral tends to characterise continental (arid) or lacustrine deposits. In marine sediments (rare) may be segregated by organisms (*rhizopods*): see J. Samoilov, *Mineral. Mag.*, 18, 1917, p. 87.

Barkevicite. Essentially a basic variety of arfvedsonite (*q.v.*) rich in ferrous iron and alkalis and implying contribution to deposit in which it is found of alkaline igneous rocks, e.g. nepheline syenite and associated pegmatite.

Basaltine. This mineral implies oxidation of the iron in ordinary hornblende. "This change occurs in nature when common hornblende

is heated to about 800° under oxidising conditions, as in certain lava flows" (A. N. Winchell). Basaltine in sediments generally indicates contribution from basic volcanic rocks such as basalt and basaltic lavas.

Bastite. Essentially a secondary product (coarse form of antigorite) (*q.v.*) always pseudomorphous after rhombic or monoclinic pyroxene. Formed in hydrous or hydrothermal environments and persistent in sediments whose parent-rocks (usually serpentine) are close at hand.

Beidellite. This mineral with nontronite (*q.v.*) forms an isomorphous series. It tends to occur in "the finest colloid fractions of clays which are dominantly composed of other clay minerals" (R. E. Grim and R. H. Bray, *Journ. Amer. Cer. Soc.*, 19, 1936, p. 311). Essentially a constituent on recent clays and soils and often associated with kaolinite (*q.v.*) montmorillonite (*q.v.*) and halloysite (*q.v.*). Possesses a high base exchange capacity. Both feldspar and ferromagnesian minerals may alter readily to beidellite under suitable conditions, *e.g.* by action of solfataric solutions. Decomposition of zeolites is another mode of origin.

Benitoite. A very rare vein-mineral formed in glaucophane schist and similar rocks and only to be anticipated in sediments suitably derived.

Biotite. If in quantity and fresh, often implies occurrence in "sealed" deposit, especially lenticular sandstone in clay or shale; in porous deposit rapidly hydrated; this change may be suggested by presence of minute but perfect zircon crystals (thus released), providing contrast in type with the zircon characteristic of the deposit. Brown variety more stable than the green in sediments.

Bronzite. A variety of enstatite (*q.v.*).

Brookite. See under *Ilmenite*.

Bytownite. This is the rarest member of the plagioclase feldspar group, found in basic plutonic and volcanic rocks. It is still rarer in sediments and easily undergoes alteration on release from parent rock.

Calcite. Seldom detrital in sediments of geological age; a highly stable product of the "lime environment"; derived from percolating lime-bearing solutions or from organic sources; suggestive of aqueous rather than terrestrial environment, though may be formed under fluvial and lacustrine conditions. Too ubiquitous to be indicative of very precise environments.

Cassiterite. Locally significant of distributive province; durable except under hydrothermal conditions (impregnation of porous sediment by thermal waters). Has been recorded from Triassic deposits (P. G. H. Boswell).

Celestite. When in association with other saline deposits, *e.g.* anhydrite, gypsum, rock-salt, also with limestone, the presence of this sulphate points to much the same environmental conditions as do those deposits. It can be formed directly from sea-water with or without the action of organisms. In association with freshwater marls etc., it implies direct precipitation from those waters, the ultimate source of the strontium being igneous rocks. The presence of this mineral is to be anticipated in the above-mentioned rocks, but it appears to be sporadically developed and not in itself significant of any peculiar conditions beyond those noted.

Ceylonite. Of no special stratigraphical significance; may be anticipated where corundum, andalusite, sillimanite and kyanite are all present; under some conditions its absence may be due to alteration to steatite.

Chalcedony. Seldom detrital; more commonly the cryptocrystalline product of secondary silicification by infiltration of aqueous solution; often of debatable origin and significance in sediments. The same applies to varieties, *e.g.* agate, jasper etc. (p. 262) when identified in sediments.

Chert. In a majority of cases indicative of marine origin of the deposit in which it is found; generally of organic derivation, *e.g.* *radiolaria*, sponge spicules. More rarely it may occur as a siliceous replacement of original calcium carbonate in the form of fossil shells, or as representing deposition of colloidal silica in calcareous ooze while the latter is accumulating on the sea-floor. Where chert is common in a detrital sediment, contribution from (usually) shallow water limestones is suggested.

Chiastolite. Like andalusite, of which it is a variety, an anti-stress mineral, but probably less stable chemically and physically than that species; unlikely to survive redeposition; under conditions of hydration, prone to alteration to mica, presumably with separation of carbonaceous matter; to be anticipated locally in semi-porous, fine-grained sediments.

"Chloritic Matter." Prevalent chloritic matter in sediments is suggestive of original occurrence of ferromagnesian minerals, *e.g.* augite, hornblende, biotite etc. It is doubtful whether any precise member of the chlorite family is commonly identifiable as a detrital mineral, owing to possible variation in composition. Chloritisation has probably proceeded in most cases before the original species reaches the sediment; incipient alteration noted in detrital augite, hornblende, biotite, tourmaline (?) suggests, however, contemporary change. Chloritic products chiefly noted in "open," coarse sediments to which meteoric waters have easy access; they are far less common in "sealed" deposits.

Chloritoid. In so far as sediments are concerned, ottrelite seems to be far less stable than chloritoid, but primarily little seems to be known of the real composition and genesis of these minerals. Some of the Brittany chloritoid is suggestive of development *in situ*; in other cases it is clearly derived. As a local stress mineral, its occurrence in sediments is hardly suggestive of more than provenance.

Chromite. Tends to localise the source of the sediment in which it is found, but has little, if any other stratigraphical value.

Chrysotile. Dimorphous with antigorite (*q.v.*), with which it is often associated; implies derivation from ultrabasic rocks, *e.g.* serpentine rock. Formed as a result of hydrous alteration of magnesium-rich minerals, or more rarely as a product of dedolomitisation following metamorphism of siliceous dolomite.

Clinochlore. A prominent member of the chlorite group, but not as abundant in sediments as penninite. Invariably of secondary origin, generally after ferromagnesian minerals. May indicate contribution from volcanic rocks which have been subjected to hydrothermal alteration, or from schist or phyllite.

Clinzoisite. Essentially a secondary product of alteration of ferromagnesian minerals or of lime-soda plagioclase feldspar; or may indicate derivation from metamorphosed, impure limestones in contact zones with basic igneous rocks. Commoner than zoisite (*q.v.*).

Collophane. Occurs both authigenic and detrital in sediments, implying phosphate deposits or derivation from same. "Considering its softness and comparatively easy solubility, it is not to be supposed that collophane in appreciable quantity could survive either transportation over a long distance or weathering through a long period of time . . . it may occur rather abundantly as a detrital mineral where source beds are near at hand and weathering has not been too thorough." (J. H. C. Martens, *Amer. Mineral.*, 17, 1932, p. 153.)

Cordierite. An unstable mineral, especially in sediments; in a hydrous, alkaline environment it changes to micaceous pseudomorphs

such as pinite; it may be produced in sandstone by "vitrification" due to contact with igneous rock-magma (H. Bücking, quoted by F. W. Clarke, *Data of Geochemistry*, 1924, p. 410). It tends to be preserved in impervious deposits not far removed from source of origin. Has been recorded from Carboniferous and Triassic deposits (P. G. H. Boswell).

Corundum. Although primarily a stable species, prolonged action of percolating water may produce alteration products, e.g. diaspore; dissolved salts in such waters may, by coincident action, produce various compounds, e.g. muscovite, chloritoid, zoisite etc. It is suspected that such changes are capable of taking place in porous sedimentary environments, but to what extent is unknown; this may account for the increasing rarity of corundum in deposits of geological age. It tends to be commoner in marine than in other types of sediment: a saline environment may retard alteration, hence its preservation, but further observations on detrital occurrences are required.

Crossite. A rare and localised amphibole associated with schists and contact altered rocks of which, in sediments, it is accordingly indicative.

Cymatolite. A name given to an intimate admixture of albite and muscovite resulting from decomposition of spodumene (*q.v.*) which has been influenced by soda-bearing solutions and reactions due to potassium salts. Not a specific mineral and only to be anticipated where spodumene is diagnosed.

Delessite. A ferriferous form of penninite (*q.v.*).

Diallage. A variety of augite or diopside characterised by prominent orthopinacoidal parting, giving the mineral a lamellar or fibrous habit; particularly characteristic of gabbros, to which source, when found in sediments, it is usually traceable. Not to be anticipated in deposits of geological age or far removed from parent rocks.

Diamond. Rare in sediments of geological age; essentially a localised river-gravel mineral of ultrabasic igneous rock origin; less commonly from pegmatite veins and quartzose conglomerates.

Diaspore. Frequently an alteration product of corundum in aqueous environment. Also commonly occurs in bauxite deposits. In association with hydrous sulphates implies derivation from volcanic rocks. May also be produced by decomposition of sodalite.

Dickite. Hydrated aluminous silicate, closely allied with kaolinite, but of rarer occurrence, chiefly associated with ore deposits. Also characteristic in certain types of clay.

Diopside. In sediments is prone to alteration to minerals of the chlorite group, calcite etc., though in "sealed" deposits, fresh grains may be preserved; probably would not survive prolonged transport or re-deposition.

Dolomite. In detrital sediments almost invariably authigenic and characteristic of, but not confined to shallow water marine deposits; where dolomite is common and calcite rare, organic origin in a "magnesian sea" may be suggested; alternatively precipitation from percolating waters in continental deposits is possible, e.g. where a magnesian limestone is laid under contribution; in this connexion it is noted that Palæozoic limestones tend to be more highly magnesian than those of younger geological age; thus an abundance of dolomite in a detrital sediment may presuppose the existence of Palæozoic limestone as a source of the magnesian carbonate. Absence of the lime carbonate would seem to indicate subsequent leaching action, facilitated by access of meteoric water through porous deposit; close textured or impervious rock, e.g. marl, silt, favours presence of both calcite and dolomite and this is frequently observed. Dolomitic limestone overlying porous detrital

deposits may similarly contribute to the formation of the mineral in those sediments.

Dumortierite. Frequently significant of pegmatitic parent-rocks; also to be expected in association with kyanite, sillimanite, andalusite etc.

Enigmatite. A rare species derived from soda-rich syenites and trachytes.

Enstatite. Not a mineral to survive much mechanical or chemical stress; by hydration it alters to steatite and minerals of the chlorite group, the former and often the latter tending to be lost in the process of sedimentation.

Epidote. Both detrital and the product of a destabilising environment; in the latter case derived from ferromagnesian minerals, sometimes garnet and invariably associated with chloritic matter; detrital epidote is frequently unaccompanied by chloritic minerals; the authigenic variety is consistent with continental and lacustrine deposition, detrital epidote being more frequent in marine deposits. Has been recorded from Longmyndian (Pre-Cambrian) deposits (P. G. H. Boswell).

Fayalite. Not common in sediments, but may occur locally where acid volcanic rocks are laid under contribution. In recent and contemporary deposits, alluvium, dust etc., not infrequently derived from disintegration of furnace slag.

Flint. Particles observed in detrital sediments imply derivation either directly from chalk deposits or indirectly through the medium of later-aged sediments or disintegration of gravel. Flint reacts easily to its environment and weathers accordingly. In large fragments or pebbles, much may be learned of the probable history of any particular occurrence from a close study of patination, shape, indentations, variation from surface to centre, proportion of granular chalcedony to opaline silica, presence of organic structures, e.g. sponge spicules.

Fluorite. Undergoes alteration in a sedimentary environment invaded by percolating water charged with bicarbonate or alkaline carbonate; sometimes authigenic, cementing sandstone (W. Mackie), or may be formed by replacement of lime carbonate by percolating fluoride solutions in porous sediments; may be significant of fluvial or terrestrial deposits, but this is not invariable. Generally indicative of highly mineralised provinces, often (in Britain) of particular developments of Carboniferous Limestone. Colour may, in conjunction with other varietal features, be suggestive of provenance.

Fuchsite. An uncommon species in sediments and significant generally of micaceous rock derivation. Essentially the product of a quartzite or schist province.

Galena. May impregnate porous sandstones, e.g. Keuper Waterstones, Cheshire, otherwise mainly of alluvial derivation in proximity to sulphide deposits.

Gastaldite. A closely related species to glaucophane having much the same environmental significance and alteration tendencies.

Gibbsite. Origin often traceable to corundum, from which it is formed by action and contact of saline percolating water. Frequently associated with bauxite deposits; may also be directly derived from decomposition of feldspar.

Glaucinite. Where organic structure is evident, marine origin of its environment is seldom in doubt; derived glauconite, however, does occur, usually partially limonitised and lacking organic character (e.g. Wealden deposits); frequently significant of stratigraphical breaks, e.g. glauconite and phosphate development coincident with subaqueous un-

conformity between *Dictyonema* shale and glauconite shale, Lower Ordovician, Scandinavia (W. G. Fearnside, *Geol. Mag.*, 1907, p. 257, 295); also similar association at junction between Chattanooga shale and overlying Carboniferous, Tennessee, U.S.A. (C. W. Hayes, *U.S. Geol. Surv.*, 16th Ann. Rep., 1895, p. 611; 17th Ann. Rep., 1896, p. 523); "... the more significant breaks in a stratigraphic series are likely to be marked by the occurrence of autochthonous glauconite, in many instances associated with, directly above the break or rarely more than a foot or two above it" (M. I. Goldman, *U.S. Geol. Surv.*, Prof. Pap., 129, 1921, p. 1: also "Association of Glauconite with Unconformities," *Bull. Geol. Soc. Amer.*, 32, 1921, p. 25; also *Science*, 56, 1922, p. 171). Where glauconite and phosphate occur, the latter predominates in littoral facies, glauconite in off-shore shallow water facies, i.e. continental shelf (F. Andersson, *Bull. Inst. Univ., Upsala*, 2, 1895, p. 133). Colour may be significant, depth of colour varying inversely with geological age: darkest green in Cretaceous and Tertiary beds, lighter green in Palæozoic, e.g. Cambrian; survival of "ancient" glauconite mostly due to presence of impervious cover-rock. Both fresh and limonitised glauconite may be present in arable soil, owing its formation to adsorption of potassium compounds in this environment, the adsorptive media being soluble (colloidal) silica and colloidal ferric hydroxide. (L. Cayeux, *Ann. Soc. Géol. du Nord*, 34, 1905, p. 146.) The possibility of some soil-glauconite being derived by circulating waters is to be noted. Gravity may be significant:—higher gravity may indicate slightly limonitised glauconite of inorganic origin, therefore not necessarily in marine deposits; lighter gravity is more typical of "foraminiferal" glauconite, not so prone to alteration (gravity range 2.25 to 2.92). A species of great stratigraphical value in all circumstances (cf. A. F. Hallimond, *Mineral. Mag.*, 19, 1922, p. 330). For other references see Chapter IX, p. 289.

Glaucofane. A stress mineral of sporadic occurrence in sediments; may possibly be authigenic (decomposition product), especially if fresh (B. Koto, *Journ. Coll. Sci., Tokyo*, 1, 1887, p. 85). When detrital, often shows chloritic alteration; degenerates with geological age, being observed mostly in middle Tertiary to Recent deposits, especially Miocene marls and silts of widely separated countries.

Goethite. Contains 89.9 per cent. of Fe_2O_3 and is a common ferric hydrate derived from decomposition of rocks, precipitation from solution, being both by chemical and organic agency. Seldom of special significance in detrital sediments, unless interpreted in terms of other criteria, e.g. stratigraphical evidence, mode of occurrence of containing deposit etc.

Graphite. Much of the so-called graphite in sediments (usually recent or alluvial) is probably amorphous carbon derived by mechanical disintegration from minerals containing carbon inclusions, or else from hydrocarbon impregnation; otherwise of little geological significance.

Grossularite. Generally significant of derivation from contact metamorphosed crystalline limestone confirmed by presence of idocrase or wollastonite; more rarely may pseudomorph vesuvianite or gehlenite (melilite group). Not as stable when released as almandite and liable to alter partially to epidote, chloritic minerals or calcite.

Gypsum. Varied genesis; a favourable environment is that under which pyrite by oxidation can react with calcareous rocks; it may be fundamentally of marine origin, i.e. concentration of saline waters by desiccation; deposition from infiltrating freshwater solutions containing lime-salts will determine its appearance in many porous deposits; often of considerable stratigraphical significance. (See also *Anhydrite*.)

Halloysite. An amorphous constituent of certain residuary clays and significant of probable association with species such as beidellite, montmorillonite.

Hematite. Tends to be common only where sediment is "sealed" or where infiltration of meteoric water is prevented by impervious cover, otherwise rapidly hydrated to limonite.

Hercynite. The iron-spinel of rare occurrence and doubtfully recorded in sedimentary rocks.

Hiddenite. See under *Spodumene*.

Hornblende. Sometimes a difficult mineral to interpret; is freshest in "sealed" deposits, much chloritised in porous sediments; the brown variety seems to be much less stable and may be a criterion of geologically recent formations; green hornblende has a much greater time-range and would seem to be favoured by marine environments, e.g. Ordovician, Upper Lias-Inferior Oolite, Portland Sand, Aptian, Eocene, Miocene, Pliocene.

Humite. Scanty records in sediments indicate derivation of this mineral from dolomitic limestone, especially in contact-altered zones where magnesium silicates have developed. A rare species and to be anticipated only in favourable environments in which such provenance is in evidence.

Hyalite. See under *Opal*.

Hypersthene. As for *Enstatite* (q.v.).

Iddingsite. A rare species as yet recorded only from river sands and certain soils. Unstable in acid environments.

Idocrase. See under *Vesuvianite*.

Ilmenite. "The titanium minerals are . . . closely connected with one another, and transformations are possible in almost every direction" (F. W. Clarke, *Data of Geochemistry*, 1924, p. 355). This concerns ilmenite, anatase, rutile, brookite, titanite, leucoxene, possibly perovskite (unrecorded as detrital) and locally pseudo-brookite (a rare accessory of volcanic rocks, also unrecorded in sediments). Majority of anatase grains are authigenic, i.e. generated *in situ* at the expense of ilmenite or other titanium species; brookite is sometimes authigenic, though it alters to rutile in suitable environments; its comparative scarcity may be due to this fact, much of the large, ill-shaped, dirty-brown rutile possibly representing this reaction; rutile is both derived and authigenic, similarly titanite and leucoxene; the geochemical mechanism of these transformations may be reasonably clear, but the selective operation of any particular tendency in a sedimentary environment is not so obvious and requires investigation. The ilmenite-leucoxene ratio alters in favour of the latter with increasing geological age of the enclosing sediment, but seems to bear little relationship to the occurrence of the oxides or titanite; a reciprocal relationship has, however, been noticed between titanite on the one hand and anatase and brookite in the same deposit on the other (P. G. H. Boswell, *Geol. Mag.*, 1924, p. 267). "Biotite altering beneath a capping of turf and in a sour water environment is likely to undergo complete disintegration, and it appears at least possible that (a) its decomposition products include a more or less colloidal complex of titania and silica, and that (b) the silica and titania may slowly disengage themselves and become crystalline: the silica may expend its potential energy in repairing and extending quartz grains, or in initiating new ones; in a similar way, titania may apply itself to anatase. It is also possible that the alteration of ilmenite to granular anatase proceeds via a complex of hydrated ferric oxide and hydrated titania, and anatase nuclei thus authigenically produced could receive extensions in the manner suggested

above" (A. Brammall and H. F. Harwood, *Mineral. Mag.*, 20, 1923, p. 24). The instability of aliothigenic biotite under certain sedimentary conditions is capable of initiating a similar mechanism and enquiry into the provenances of British sediments rich in transparent titanium minerals in most cases points to the presence of sufficient black mica for the purpose in the parent-rocks concerned. The development of anatase is facilitated by high porosity and ill-graded sediment, implying facility of "sour water" circulation. The generation of leucoxene and titanite (according to A. Cathrein synonymous terms—see *Zeitschr. Kryst. Min.*, 6, 1882, p. 244) suggests a similar environment and it is observed that leucoxenic alteration is at a maximum in coarse sediments; authigenic titanite may be initiated with the formation of titanium-bearing chloritic minerals from decomposed amphibole-rich parent-rocks, since chlorite is often observed in concentrates in which titanite is conspicuous; the presence of lime is, of course, essential. Where lime is absent or at a minimum, especially in an iron-rich environment, the ilmenite—rutile—anatase—brookite tendency (in order of decreasing frequency) seems to predominate; in a neutral environment the leucoxene—titanite—perovskite tendency may be strong, but there is difficulty of achievement, certainly of persistence, in the case of the two latter species, attested by their scarcity in detrital deposits; alternatively, they may be formed initially in a sedimentary environment, but owing to chemical instability or unfavourable "atmosphere," the titanite—rutile—ilmenite tendency may be promoted. Careful observation of the occurrence and association of the titanium minerals in all kinds of sediments is needed before their individual or collective significance can be fully appreciated.

Indicolite. See under *Tourmaline*.

Jasper. See under *Chalcedony*.

Kaolinite. Known chiefly as an alteration product of felspathic minerals, sometimes by pneumatolysis, but in sediments by the action of humous acid (if near the surface) or of percolating water and carbonic acid. Frequently accompanied by sericitic mica. Rare as an individualised mineral in sediments; usually noted as a decomposition product in deposits which are ill-graded or "open"; is not confined to, and is often totally absent from, argillaceous rocks. (See R. Schwarz and R. Walcker, *Zeit. f. anorg. chem.*, 145, 1925, p. 304.)

Kunzite. See under *Spodumene*.

Kyanite. A stress mineral. Chemically stable and resistant to acidulated percolating waters (more so than andalusite or sillimanite in sediments), to which its remarkable persistence may be ascribed. Susceptible of disintegration under mechanical stress and may thus be an indicator of the intensity of the forces implied, largely due to its prevalent cleavages.

Labradorite. In certain circumstances prone to decomposition by percolating waters charged with carbon dioxide, whereby calcite and free silica are formed. Other forms of alteration (sometimes detected in partial phase in isolated grains) include sericitisation or kaolinisation "Saussuritisation" (p. 305) is prominent with labradorite derived from basic igneous rocks (e.g. gabbro). Seldom survives "fresh" in sediments far removed from parent-rocks.

Lawsonite. Probably of wider spread occurrence in sediments than records imply. Generally secondary, derived from lime-soda plagioclase, especially in "saussuritised" gabbro environments. Occurs in gneisses and schists. A normal mode of development would appear to be by hydration of anorthite.

Lepidolite. In detrital deposits may be primary or secondary after muscovite (q.v.).

Lepidomelane. Iron-rich *Biotite* (q.v.).

Leucoxene. See under *Ilmenite*.

Limonite. Commonly implies oxidation and hydration of iron-ores such as pyrite, pyrrhotite, marcasite and is also formed from magnetite, hematite, ilmenite and other iron-bearing minerals. Oxidation of sulphidic iron-ores produces firstly soluble sulphate, afterwards precipitated as hydroxide; process aided by carbonic acid in percolating water; organic acids also potent in this respect. In detrital sediments limonitisation proceeds where the rocks are porous and where iron-bearing solutions have ready access to them; or in a "sealed" environment alteration of original iron sulphides or oxides may take place slowly. Limonite in detrital sediments is frequently prolific in proximity to glauconite-bearing rocks, implying the formation by alteration of the glauconite. Limonite is so ubiquitous in sediments and its genesis is so varied, that in the absence of other evidence it is seldom of any special significance.

Magnesite. Implies formation by (a) decomposition of ultrabasic igneous rocks such as peridotite, serpentine, by action of water charged with carbon dioxide, (b) replacement of existing limestone (calcium by magnesium), (c) chemical precipitation in which magnesia-bearing solutions are in contact with carbonates. Presence in sediments (or associated with them) more often than not implies subaërial, as distinct from marine conditions of formation.

Magnetite. Pure magnetite is far less common in detrital sediments than is generally thought; usually it is detrital, but it may also result from alteration of marcasite and pyrite (C. R. Van Hise) or from the oxidation of siderite. It is most characteristic of fine-grained, semi-porous deposits where infiltrating solutions are less potent.

Marcasite. The unstable isomer of pyrite and nearly always authigenic. Best preserved in a neutral environment or in the presence of lime; its organic origin is frequently suggested by its occurrence in association with fossil shells almost invariably in marine deposits; an hermetically "sealed" environment aids its preservation.

Melanite. The rare titanium-bearing garnet (also known as "schorlomite") known particularly in alkali syenites (e.g. Assynt complex, Scotland) from which rock-type its derivation in sediments may be inferred. Frequently accompanied by feldspathoid minerals, e.g. nepheline (the latter probably represented in sediments by its decomposition product "cancrinite").

Microcline. A valuable indicator of climatic conditions attending deposition of the sediment in which it occurs (p. 496).

Monazite. The alteration of this mineral to an aggregate in which cerium oxide is conspicuous tends to be superficial, but in deposits of geological age seems to proceed under conditions implying humid, estuarine environment; fresh, unaltered monazite, though characteristically "worn," is of little significance other than of provenance.

Montmorillonite. Particularly characteristic of deposits such as Fuller's earth. A complex hydrated aluminous silicate produced by alteration of mica, feldspar etc. Possesses marked adsorption and base-exchange capacities.

Muscovite. When detrital, its disproportionate size relative to associated constituents is noteworthy and significant of its buoyancy, especially in an aqueous medium. May be authigenic, formed from feldspar, topaz, andalusite; or may represent certain feldspathoid minerals. Some muscovite observed in sediments represents bleached biotite (cf. optical

properties), implying action of acidulated solutions, whereby iron oxide and alkalis are removed and hydration promoted. *Sericite* is invariably secondary and is a stress mineral; white mica is more prolific in fluvialite and estuarine arenaceous sediments than in similar deposits of marine origin or conversely in marine, rather than in fluvialite or estuarine clays.

Nephrite. As for *tremolite* or *actinolite* (q.v.).

Nontronite. A rare alteration product characteristic of certain residuary clays often associated with montmorillonite, beidellite. In some cases it may be indicative of original alkaline petrographic province. May also be derived from wollastonite.

Oligoclase. Probably the most stable of the plagioclase feldspars in surviving the sedimentary cycle, kaolinisation being less common than with albite or andesine. Under hydro-thermal conditions, the normal change is to sericitic mica. In sediments it is inferential of sub-acid and intermediate igneous rock provenance.

Olivine. Fresh, unaltered detrital olivine is rarely, if ever, found in sediments of geological age, decomposition to one of the chlorite species (e.g. in serpentine), steatite, epidote etc., being easily achieved, especially in a hydrous environment. It is thus characteristic only of Recent deposits (shore sands and alluvials) not far removed from source of origin, Essentially an anti-stress mineral.

Omphacite. As for *Diopside* (q.v.).

Opal. Invariably of secondary origin implying a reconstitution of certain rock-forming silicates under stress of hydro-thermal metamorphosis; or deposited from solution in "hot spring" environments. More rarely of organic origin.

Orthoclase. A valuable indicator of climatic conditions attending deposition of the sediment in which it occurs. Does not long survive a hydrous environment, especially if percolating waters are acid or if any associated sulphide ores are undergoing oxidation whereby acid may be liberated *in situ*. Meteoric water containing carbon dioxide also attacks it. Such alteration is usually indicated by the presence of kaolinite, mica or hydrous silicates of alumina; mica will not be formed if alkalis have been removed. In the presence of lime and iron, epidote or zoisite may form. An anti-stress mineral. The variety *Sanidine*, when identified in sediments, suggests derivation from acid volcanic rocks, e.g. rhyolite, trachyte etc.

Ottrelite. Essentially a product of schists and phyllites, but apparently (from the records) less stable than chloritoid; consequently it does not persist long in sediments. Tends to alter to one or other of the chlorite group of minerals.

Penninite. Invariably of secondary origin, generally the product of hydrothermal alteration of aluminous ferro-magnesium minerals such as augite, hornblende, biotite, epidote etc.

Periclase. A rare species tending to alter easily to hydro-magnesite or chloritic minerals. In other hydrous environments, brucite is formed.

Phlogopite. Occurrence in sediments generally implies release from dedolomitised crystalline limestone. Commonly associated with forsterite and diopside in such circumstances.

Picotite. Of no apparent significance save as an indicator of parent rocks.

Piedmontite. A rare species derived principally from schists and gneisses; often of secondary origin.

Psilomelane. Indicates derivation from secondary manganese deposits and commonly associated with pyrolusite. Often occurs with sedimentary iron-ores from which provenance it is frequently traceable in sediments in which it is identified.

Pyrite. Is most characteristic of impervious clays, shales and muds where it is usually authigenic and suggestive of organic origin. In a reducing environment, especially under marine conditions, sulphates are converted to sulphides by the decomposition of organic matter; in the presence of CO_2 sulphuretted hydrogen is formed which, by reaction with iron silicates, forms pyrite, marcasite etc. Alternatively, bacterial influence may account for the H_2S . The frequent occurrence of pyritised casts of micro-organisms is suggestive of the mechanism above outlined. The occurrence of pyrite bears an interesting relationship to the colour of the sediment containing it, whereby considerable light may be thrown on the environment of sedimentation: it is rare in red rocks, usually inferential of oxidising conditions and frequently the colour of terrestrial (fluvial and aeolian) deposits; it is sporadic in blue or bluish-grey rocks, especially clays, usually suggestive of reducing reactions in excess of oxidising influences; it is most common in black or blackish-grey clays or muds formed in a reducing environment, often implying biochemically toxic conditions; in green rocks it tends to be rare or absent where the colour is due to chloritic products (resulting from decomposition of ferromagnesian minerals), in which case the chloritic matter is apparent; more common where the colour is due to glauconite. These circumstances are exemplified by the Stockdale Shales (Silurian) of the Lake District (J. E. Marr, *Quart. Journ. Geol. Soc.*, 81, 1925, p. 113), where benthonic organisms are absent in the black muds (pyrite and carbon common), rare in the green and some of the red muds, fairly abundant in the blue and part of the red muds; absence, rarity or observed dwarfing of these organisms is ascribed to toxic influences, sulphuretted hydrogen or iron hydrate. Thus pyrite, apart from its own significance, should be interpreted in conjunction with organic evidence if available; this mineral, together with its oxidation products, will frequently throw a flood of light on the nature of the environment from both biological and geological points of view.

Pyrolusite. A product of infiltration, usually observed on joint planes of calcareous rocks. In some cases it may be traced to swamp deposits associated with limonite, from which it is transported into underlying rocks by descending meteoric waters, but often its origin in sediments is obscure.

Pyrope. Occurrence in sediments suggests derivation from ultra-basic igneous rocks. Does not tend to survive far after release from parent rock, being readily altered to kelyphite (sometimes a fibrous intergrowth of amphiboles and feldspar, but often a complex mixture of amphiboles and pyroxenes). In anhydrous environments tends to alter to one or other of the chlorite group of minerals. Most commonly confined to alluvial deposits not far removed from source of origin.

Pyrophyllite. One of the kaolinite group of minerals occurring chiefly in crystalline schists. Comparatively rare in sediments.

Pyrrhotite. The origin of this mineral in detrital sediments is not always clear, but it tends to occur only in "sealed" sediments beyond the reach of oxidising or acidulated waters of meteoric origin, though it is itself almost invariably authigenic; probably formed as a result of biochemical processes.

Quartz. This essential mineral of detrital deposits is significant of environment chiefly by reference to its form (nature and degree of abrasion), while a study of its inclusions is often of prime importance in tracing the source of the deposit concerned.

Riebeckite. A rare, unstable soda-bearing amphibole which tends rapidly to alter with release from parent rock. It is consequently rare in sediments of geological age, but may be expected to persist in recent deposits, especially in detrital deposits protected from aqueous infiltrations.

Ruby. See under *Corundum*.

Rutile. See also under *Ilmenite*. Rutile is a possible stress mineral. Perfect euhedral forms in detrital sediments are probably authigenic, but derived rutile, often much fractured, is met with universally and particularly in æolian deposits.

Sanidine. See under *Orthoclase*.

Sapphire. See under *Corundum*.

Selenite. The crystalline form of gypsum is particularly characteristic of clay environments where it persists either as individual crystals or more commonly as complex clusters of twinned types. With the weathering of the clay, crystals rapidly disintegrate on account of their soft and hydrous character. In other environments, it can suffer dehydration to anhydrite or more rarely reduction to native sulphur. See also under *Gypsum*.

Serpentine. See remarks in Chapter IX, p. 335, and refer to *Antigorite* and *Chrysotile*.

Siderite. Frequently significant of a fluvatile or lacustrine environment, especially in fine silts and clays in which vegetable organic matter is present. Infiltrating waters charged with carbonic acid may, in the presence of organic matter, result in the formation of siderite, though in porous rocks calcite and limonite are the more likely products. E. Spencer suggests another mechanism (*Quart. Journ. Geol. Soc.*, 81, 1925, p. 687), "that the iron compounds present in solution as soluble carbonates, humates or hydrolised and possibly colloidal hydrates, were absorbed by the fine-grained and partly colloidal sediments, and carried down with them during deposition." Clay-ironstone is a precipitate deposit tending to form about organic nuclei under terrestrial (as opposed to marine) conditions. Oolitic forms of siderite are frequently accompanied by the mineral chamosite, an iron silicate, as in the Cleveland deposits (*Sum. Prog. Geol. Surv. Gt. Brit.*, 1922; see also A. F. Hallimond, *Mem. Geol. Surv., Spec. Rep. Min. Res. Gt. Brit.*, 29, 1925) and imply weak carbonation; strong carbonation is productive of clay-ironstone; spherulitic siderite can only be produced in the absence of chamosite (E. Spencer). Thus a detailed study of siderite in sediments may be highly suggestive of their mode of formation and environment.

Sillimanite. A highly stable species, but of little significance save as an indicator of provenance.

Spessartite. Rare in sediments, but may occur where certain types of schists or rhyolite contribute to their formation. In some environments is known to alter readily to biotite.

Sphalerite (Zinc Blende). Tends to localise the deposit in which it is found. E. F. Newton draws attention to its unusually abundant occurrence in roughly rounded aggregates up to 0.25 mm. in diameter in the Cretaceous Fuller's earth of Surrey and to its rarer occurrence in the Jurassic earths of England (*Proc. Geol. Assoc.*, 48, 1937, p. 179, 184). H. H. Thomas also noted the occurrence of zinc blende and galena in the English Mesozoic clays and stated that "where these two sulphides are met with, they always occur surrounding or replacing the soft part of some organism" (*Geology of Ore Deposits*, 1909, p. 328). He further pointed out (*op. cit.*, p. 321) that zinc sulphide is normally precipitated in alkaline solutions, but under increased pressure may also be produced in a feebly acid one.

Sphene. See under *Ilmenite (Titanite)*.

Spinel. Highly stable species in sediments generally implying derivation from crystalline limestone or schist. See also under *Ceylonite*, *Picotite*, *Chromite*, *Magnetite*.

Spodumene. The lithia-bearing pyroxene, chiefly significant for its association with coarse pegmatites to which source its origin in sediments

may often be traced. Very susceptible to alkaline solutions by which it is changed into albite, muscovite etc. An anti-stress mineral. *Hiddenite* is the rare emerald-green, *Kunzite* the lilac variety.

Staurolite. A stress mineral. Is frequently suggestive of provenance, but is independent of facies and not inferential of any particular sedimentary environment. Pre-Armorican record from Llandovery (Silurian) of the Midlands (P. G. H. Boswell).

Steatite (Talc). Occurs chiefly in schists associated with chlorite minerals and iron ores. Also occurs in serpentine rocks as veins and filling cavities from which it is easily released to contribute to nearby recent sediments.

Strontianite. A local species to be anticipated only in environments where the mineral is known in veins (generally in limestone).

Sulphur. To be anticipated in sedimentary deposits where it occurs as a sublimate in volcanic regions, particularly where subject to recent activity. Also prevalent in gypsum deposits in similar environments or may be traceable to hydrogen sulphide emanations, mineral springs, crude petroleum or other bituminous matter.

Talc. See under *Steatite*.

Thulite. As for *Zoisite* (q.v.).

Titanite (Sphene). See under *Ilmenite*.

Topaz. Frequently occurs under the same conditions as andalusite, but is more stable than that mineral and has a wide stratigraphical range; noted in Upper Silurian deposits. In an alkaline environment (infiltrating alkali-bearing solutions) a change to muscovite (damourite or sericite type) is possible.

Tourmaline. An ubiquitous detrital species on account of its stability, though under certain conditions is liable to micaceous and chloritic alteration. May survive more than one erosional cycle, when its worn character, together with other criteria may be significant. In some cases there is reason to believe that this mineral is authigenic. *Indicolite* is a local indigo-blue variety.

Tremolite. A stress mineral, sometimes replacing pyroxene; is not so stable as ordinary hornblende and does not survive prolonged transport or re-deposition; hence it tends to localise the deposit in which it occurs.

Uvarovite. A rare mineral in sediments. Derived from ultrabasic igneous rocks (usually chromium-bearing) or contact-altered limestones, but readily alters to chrome-bearing chloritic matter in hydrous environment.

Vesuvianite. A contact-altered limestone species associated particularly with grossularite, wollastonite and epidote and stable in sedimentary deposits derived therefrom.

Viluite. As for *Vesuvianite*.

Wolframite. Essentially a pneumatolytic vein species generally associated with cassiterite; stable but superficially weathering brown in detrital deposits.

Wollastonite. A contact-altered limestone species often associated with diopside, garnet, epidote and readily altered to calcite.

Xenotime. A problematical species in detrital sediments on account of the difficulty in its certain diagnosis; may be anticipated where monazite is prevalent, but has little other significance.

Zircon. An almost invariable accessory mineral in detrital deposits and, like tourmaline, may survive several erosional cycles; colour, zoning and inclusions are significant of provenance. See also under *Biotite*.

Zoisite. A stress mineral to be anticipated in association with hornblende, glaucophane, epidote etc., and probably more common in sediments than usually supposed.

CHAPTER XIV.

THE APPLICATION OF SEDIMENTARY PETROLOGY TO THE STUDY OF SOILS AND RELATED SUPERFICIAL DEPOSITS.

Introduction—Classification of Soils—Soil Analysis—Modern Conceptions of Soil Constitution—Mechanical Constitution of Soils—Soil Colouring—Function of Sedimentary Petrology in Soil Investigations.

Introduction.—The investigation of soils and related superficial deposits from a petrological standpoint, along the lines laid down in this volume for sedimentary rocks in general, is now an established technique. This application has attracted attention in many soil and agricultural research stations both at home and abroad with some striking results.

Efforts have been made from time to time in the past to awaken geological interest in superficial deposits, especially soils, for their own sake, but without much success. It must be admitted that advancement of knowledge of soils, more particularly as regards nature and constitution, evolved largely from the labours of the agricultural chemist and physicist. In the process of drift surveys, superficial deposits as such naturally received due recognition and study, but the uppermost soil-layers were only too frequently neglected. Certainly the resources of the modern petrological laboratory have only comparatively recently been invoked on a full scale to determine soil as a rock.

The geologist is inclined to regard soil as the inevitable blanket concealing his rocks and limiting his outcrops. His interest in it begins and ends with its larger rock-components turned up by the plough on cultivated land or exposed by some other means. Even prehistory, that happy common ground of geologist and anthropologist, denies to the soil more than recognition as a possible medium in which lie scattered human relics.

G. W. Robinson¹, in a suggestive article "Pedology as a

¹ *Geol. Mag.*, 61, 1924, p. 444.

branch of Geology," drew attention to this state of things some years ago as follows :—" We have in our own country scarcely any research in which the material (soil) is treated from a purely scientific point of view and studied in the same way as rocks have been studied by geologists." R. H. Rastall,¹ in his book "Agricultural Geology," discussing soil characteristics, says, "The agricultural value of a soil depends on a large number of factors, only some of which are within the province of the geologist. Pre-eminent among these are its mineralogical composition and the state of division of its particles; on the former subject little work has been done, and a large field of research is here open, especially with regard to the mineral character of the smaller particles."

It has frequently been the author's lot in the course of his work on sediments to investigate superficial deposits, including various types of soil, in as great petrological detail as those of geological age. Experience has shown conclusively the value attaching to this study, both from scientific and economic motives. It is the present contention that all deposits, of whatever character, lying above the solid-rock zone, are worthy of the same careful petrological attention as is accorded the more familiar strata and it is the purpose of this chapter to confirm the truth of this dictum.

Soils present a variety of difficult problems which make common research territory for the biochemist, physicist and geologist. Modern conceptions of their nature, constitution, mineralogical composition, mechanical analysis, relationship to bedrock and significance as products of contemporary or relatively recent formation, are all matters of geological concern. The application of petrographic methods is an obvious step towards the better understanding of these features, possibly towards a solution of some of the more obscure problems of soil-genetics. There is none better qualified than the sedimentary petrologist to undertake the study and contribute the data required. In fact, a liaison between the pedologist and petrologist may be said to have been long since established when we recall the extent to which mechanical analysis of sediments has been influenced by the relevant work of soil-analysts in the past.

¹ University Press, Cambridge, 1916, p. 143.

The term "soil" has in the past been and still is, variously interpreted. Technically it is the most superficial portion of the "regolith,"¹ that useful word of G. P. Merrill which covers the "entire mantle of unconsolidated material, whatever its nature or origin," as distinct from solid rock. On careful consideration, however, it will be seen that this description does not *define* soil. Instead it immediately raises the question as to where the superficial layer ends. If in every case soil directly overlay bedrock, then the problem of definition would be

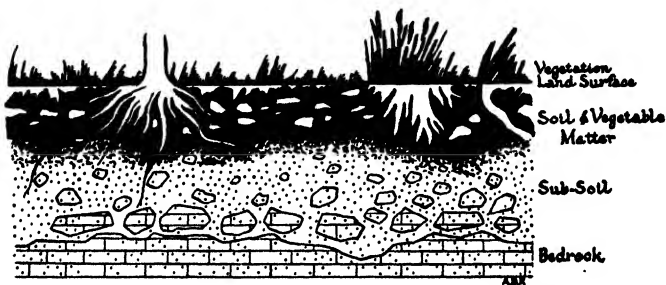


FIG. 100. Soil-Relation to Bedrock.

simple; but this is not so. It frequently happens that soils are formed *in situ* from underlying incoherent deposits, such as alluvium and in such circumstances it is virtually impossible to make a clear-cut division between the soil and superficial deposits. In its narrower and popular sense, the term "soil" is interpreted by agriculturalists and others as the medium which supports vegetable life or the cultivated zone extending from surface downwards to the limit of implement penetration. This conception of soil is again technically erroneous, since it excludes horizons normally susceptible to pedogenic processes. It is wiser, therefore, in the present state of our knowledge, to follow the practice of G. W. Robinson² and decline a definition of soil, but to emphasise instead the essential affinity of soil to superficial deposits and the corresponding need for collaboration between pedologists and geologists.

¹ "Rocks, Rock-Weathering and Soils." (Macmillan, London), 1913, p. 287.

² "Soils, their Origin, Constitution and Classification." 2nd ed. (Murby, London), 1936, p. 3.

Beneath the soil and by gradual transition lies the subsoil zone, usually an indefinite deposit of composite character. It affords a complete passage between the soil and bedrock, the lowermost layers showing obvious affinities with the latter, chiefly by the detached rock-fragments forming the "float," the higher layers having more sparsely scattered rock-fragments, lesser compaction and a marked resemblance to the soil itself (*Fig. 100*).

In drift-covered areas the soil rests on some particular type of sedentary or transported material forming part of the regolith. Actual bedrock in this case may be buried under considerable thickness of superficial deposit. Where the latter is the product of transport, *e.g.* alluvium, the soil shows affinities with it and not with bedrock. Where sedentary deposits are concerned, *e.g.* residual clay, laterite etc., some connexion is usually traceable throughout the bedrock-soil sequence. Petrological investigations serve to differentiate between such conditions and to confirm field-observations.

Classification of Soils.—It is not within the province of this book to go deeply into various systems of classification proposed for soils. Some reference must, however, be made to those aspects of the matter which have direct bearing on petrological investigations of soils or which are influenced by such research.

Actually there is much difference of opinion among soil technologists as to the most philosophical scheme applicable to all soils. Practically every classification designed so far has been subjected to severe criticism from one quarter or another. The problem reflects that with which petrologists are confronted for normal rocks or perhaps "abnormal" would be the better word, since it is essentially the abnormal types which prove obstructive to most schemes invented. Abnormalities in soils are even more pronounced than in other sedimentary deposits; added to this there is the colloidal element in soils which sometimes makes them difficult to fit with precision into any specified category.

At the outset a geological classification would seem practicable where this implied soil characters dependent on bedrock characters and petrological work would tend to support such classification. There is, however, wide divergence between

soil and bedrock in many cases, clearly in instances where soils have undergone transport. Studies in plant ecology illustrate this point forcibly.

The dry, somewhat sterile soil of wide sandstone tracts tends to favour conifers, gorse, bracken etc. Shale and clay determine the formation of colloidal soils, on the whole characterised by deciduous vegetation, *e.g.* oak, poplar etc. These observations are subject to many qualifications of latitude, climate and situation; normally, however, they hold good and exemplify the soil-geology relationship. On the other hand, calcareous rocks not infrequently support soils which, in constitution, are the antithesis of calcareous; sometimes by virtue of superficial contamination they may even be sandy and support a dominantly coniferous vegetation. The latter illustrates discordance between soil and geology and shows where a classification, based entirely on bedrock character, would at once break down.

N. M. Comber¹ writes, "But even in areas where the geological distribution of soils is of practical use, the relation of soil properties to geology is by no means perfect. This partly arises from the fact that two areas may be geologically the same and yet differ very much lithologically. It also arises from the fact that the same rock under different weather conditions will give rise to a different soil."

It is possible by petrographic means, taking into consideration the complete sequence of regolithic deposits, to differentiate between sedentary or residual and transported soils and the distinction is undoubtedly a useful one. Alternatively, if mineral components can ever be made criteria of certain definite types of soil, petrology may be anticipated to provide relevant data; but beyond this it would seem that geology *per se* has little to offer towards a comprehensive soil classification.

The purely physical classification recognises organic or humus soils, calcareous soils and mineral soils. The latter comprise the sands, loams and clays (as soils), mechanical constitution of the mineral group being the arbiter of distinction. It may be pointed out, however, that unlike normal sediments mechanical analysis cannot in itself afford an indication of

¹ "An Introduction to the Scientific Study of the Soil." (Arnold, London) 1927.

particular soil types, again for the reason that the organic matter, also what is known as the "lime status" of the soil, varies widely and must be taken into consideration.

In 1914 K. D. Glinka¹ directed attention to the importance of profile in the study of soils and the influence of his classification, based on maturity of profile development and intensity of leaching, is still discernible in more recent schemes of classification. He propounded two main groups, the immature or endodynamomorphic soils and the mature or ektodynamomorphic soils. In the former, destabilisation of the rock-forming minerals is incomplete and there may be some relationship still discernible between soil, subsoil and bedrock. In the latter, external factors of soil formation have obliterated all influence of parent rocks.

Following K. D. Glinka's work, there appeared a variety of schemes of soil classification formulated from different standpoints. Climate, pedogenic processes, character of absorbing complex and a number of other factors were adopted by different workers as a basis of classification, but none proved universally acceptable.

Latterly there has been expressed among pedologists a desire for a world-wide classification of soils to include all possible types. In 1927 C. F. Marbut² proposed a comprehensive scheme embodying in all seven stages of classification, the primary division being made between pedocals, characterised by the presence of a zone of calcium carbonate in the soil profile and pedalfers which exhibit an accumulation of sesquioxides. Further sub-divisions are made on the basis of temperature, latitude, rainfall, maturity of profile, parent material and texture. Spaces are left for the insertion of unidentified groups and thus the scheme does afford a basis for world-classification. Nevertheless, the criticism of C. F. Marbut's scheme is levied by G. W. Robinson³ that this does not include soils developed under conditions of impeded drainage which are of widespread occurrence.

¹ "Die Typen der Bodenbildung, ihre Klassifikation und geographische Verbreitung." (Gebr. Borntraeger, Berlin), 1914. Translation by C. F. Marbut (Murby, London), 1928.

² *Proc. 1st Int. Congr. Soil Sci.*, 4, 1928, p. 1.

³ *Op. cit.*, p. 354.

A. A. J. De 'Sigmond¹ also proposed a comprehensive system of classification in which he first divided soils into three fundamental groups :—organic soils; chiefly mineral soils with co-operation of organic matter; and mineral soils.

G. W. Robinson, however, is of the opinion that knowledge of the soils of the world is not sufficiently far advanced to justify adoption of a universal system of classification. He does, nevertheless, propose a system of tabulation for the well-known soils. This is based on his conviction that the "most fundamental distinction between soils depends on the character of the leaching processes."² He makes his primary division between soils with complete leaching (pedalfers), soils with incomplete leaching (pedocals) and soils with impeded leaching (hydromorphous soils). He next sub-divides pedalfers on the basis of absence or presence of acid humus and hydromorphous soils on the basis of absence or presence of soluble salts. The third stage of classification is influenced by climatic conditions and as a result of this there remain twenty-one different groups of soils. These are not, however, claimed to be final groups, since they are capable of further sub-division in the light of disturbance by cultivation, erosion etc.

Most attempts at soil classification have been inspired by the prevalent belief that comparable soils can occur in different parts of the world. The desire for correlation is natural and each system of classification proposed contributes to the ultimate goal of world-wide classification. Nevertheless, the plain fact is that at the present time knowledge of soils is not sufficiently universal to warrant stringent division into types. As G. W. Robinson says, ". . . whilst the various systems proposed may be trustworthy for the soils on which they are based, and suggestive for soils yet to be studied, the immediate task is to enlarge and intensify our information as to the constitution and genesis of the soils of different parts of the world. And if, as is probable though not proven, the soils of the world can be grouped into a finite number of classes, then the modification of existing systems and the synthesis of local classifications will ultimately lead to a world system."³

¹ *Soil Res.*, 3, 1933, p. 103.

² *Op. cit.*, p. 355.

³ *Op. cit.*, p. 361.

Soil Analysis.—Analysis of soils comprises a number of different determinations of properties according to the particular problem concerned and also to the standpoint of the investigator. It may be made chemically, petrologically and physically exhaustive, in which case the work is clearly that of large-scale fundamental research. More commonly, soil analysis tends to be routine in character, involving a limited number of more or less standardised tests which seek to define and classify a particular sample.

The technique of soil analysis to-day in many ways follows closely well-tried petrographic methods (using the latter words in their most elastic form). Certain physical and chemical methods, evolved from a vast amount of international research on soils, have been adapted and co-ordinated to the framing of a schedule of tests which, if not mandatory, is at least more or less conventional among pedologists. On the other hand, their perspective is not entirely that of the petrologist and their respective methods of approach to soil problems are by no means always identical or even comparable. Obviously the common ground is clay technology as conceived in its most modern form. It is in this field that the results of investigations of chemists, mineralogists and physicists have of late years been pooled to such material advantage to the sciences concerned.

While methods of soil analysis have been influenced by such bodies as the International Society of Soil Science, the Imperial Bureau of Soil Science, the Agricultural Education Association and the U.S. Department of Agriculture (Bureau of Soils), actual technique varies much with different investigators and there is still considerable latitude in choice of methods left to individual discretion; perhaps in the present state of our knowledge of soils this is as it should be. It is, therefore, not feasible to enumerate all the tests which are carried out by different investigators in their work on soils; neither from a petrological standpoint is such a comprehensive survey relevant. There is, however, a skeleton schedule of determinations common to practically every problem in soil analysis; this is followed in the author's laboratories and in some other research stations. It comprises some of the commonest tests undertaken on soils and comparable materials

from the results of which it is usually possible to place the sample in its proper category.

SCHEDULE OF TESTS (Soil Analysis).

Physical.

- (1) Specific gravity.
- (2) Weight per unit volume.
- (3) Porosity.
- (4) Hygroscopic moisture.
- (5) Loss on ignition.
- (6) Hydrogen ion concentration (pH reaction).
- (7) Mechanical analysis.
- (8) Colour.

Petrological.

- (9) Determination of mineral components by microscopic and other relevant methods.

Chemical.

- (10) Calcium carbonate and/or other prominent bases if suspected.
- (11) Nitrogen.
- (12) Composition of clay fraction from mechanical analysis.
- (13) Organic Matter.
- (14) Base exchange.

Reference is made elsewhere in this volume to the methods employed in determining most of the functions in the above list, hence recapitulation is unnecessary here. In what follows, however, stress is laid on mineralogical and mechanical constitution of soils, also soil colouring, regarded particularly from the sedimentary petrologist's standpoint, in order that he may appreciate such differences in technique as exist between his own normal work and that of other soil specialists.

For comprehensive treatment of the whole subject of soil analysis, the reader cannot do better than consult C. H. Wright's handbook.¹ Other references will be found in the bibliography at the end of this chapter, p. 536.

Modern Conceptions of Soil Constitution.—Investigation of numerous samples of soil has now shown that certain groups of constituents tend to be common to all types irrespective of source and mode of origin. G. W. Robinson classifies these groups as (1) mineral matter, (2) organic matter, (3) soil moisture and (4) soil air; the last two groups, however, are dependent variables and he thus conceives soil as "a three phase system with an indefinite number of components."² The solid phase

¹ "Soil Analysis: A Handbook of Physical and Chemical Methods." (Murby, London), 1934.

² *Op. cit.*, p. 9.

comprises mineral and organic matter; the liquid phase, soil moisture and the gaseous phase, soil air. Equilibrium between the liquid phase and the solid phase shifts with variations in temperature and moisture content and corresponding changes occur in the soil air. The solid phase, therefore, provides the most stable basis of comparison and study of soils.

Of the solid phase, the petrologist is concerned primarily with (1) the mineral matter in soils. In the early stages of this special application of sedimentary petrology, it was the coarser detrital minerals, certain well recognised authigenic species and also rock particles which together comprised his field of study. To-day, thanks to the rapid progress achieved in technique of determination of the finer constituents of sediments, in particular clays, the scope of his researches into soil mineralogy has been considerably and profitably widened.

The Finer Material of Soils. — The fundamental soil medium, that determining the essential characteristics of the soil itself, is the finely divided mineral matter which, until recently and for want of a better name, was termed (in part) the "colloidal complex." We now know that the inorganic part of this complex is composed of one or more of the recognised clay minerals, hence it is susceptible to treatment and investigation on the same modern lines now adopted in dealing with fine argillaceous sediments (see Chapter X, p. 374). In other words, mineralogical identification of soil components no longer stops short at the 10—5 μ range of particle sizes, but extends confidently below this into the hitherto ill-defined territory of "colloidal" as well as crystalline clay constituents, material composed essentially of particles below 0.5 μ . At risk of certain reiteration but to preserve continuity of thought, this important aspect of soil mineralogy will first be briefly examined.

The inherent difficulties to precise mineralogical interpretation of clay particles have to a large extent been overcome by application of improved optical, X-ray, spectroscopic and base exchange studies of the clay minerals.

The essentially crystalline character of these minerals was established by C. E. Marshall¹ in his researches on orientation of clay particles in an electric field; also by S. B. Hendricks

¹ *Trans. Faraday Soc.*, 26, 1930, p. 173.

and W. H. Fry¹ in their optical and X-ray examination of soil colloids. X-ray investigations by U. Hofmann, K. Endell and D. Wilm² on the montmorillonite group also had decisive bearing on the problem. Later C. E. Marshall's work³ on layer lattices and base exchange clays, involving particularly montmorillonite, beidellite and potash-bearing clays, further clarified the position, to the extent that mineralogically considered, soil petrology is now governed by a totally different outlook from that obtaining a comparatively few years ago.

The clay minerals directly concerned in these studies may be conveniently classified according to lattice type, the "1:1 fixed" including such species as:—

Dickite
Halloysite
Kaolinite
Metahalloysite
Nacrite

The "2:1 fixed" type includes:—

Pyrophyllite
Steatite

The "2:1 expanding" type includes:—

Beidellite
Montmorillonite
Nontronite

Descriptions of most of these minerals appear in Chapter IX.

Some of the above species are recognised as extremely important soil constituents, *e.g.* halloysite; others, as for instance dickite, are at present apparently of minor importance. So much research remains to be done in this field that positive data at the moment appear to be swamped by the vast amount of theory yet to be put to practical trial. It may be safely said, however, that contemporary and future research on clay minerals, whether approached from the standpoint of material of geological age or of recent accumulation, must inevitably influence, if not profoundly revolutionise, our conceptions of soil behaviour, constitution and structure. Appropriate references in extension of the above *résumé* of modern studies of the finer material of soils will be found in the bibliography at the end of this chapter (p. 536).

¹ *Soil Science*, 29, 1930, p. 457.

² *Zeit. Kristallogr.*, 86, 1933, p. 340.

³ *Zeit. Kristallogr.*, 91, 1935, p. 433.

The Coarser Material of Soils.—In so far as this can be defined in terms of definite minerals, the coarser constituents of soils are fundamentally the rock-forming species, their decomposition products and the stable accessory, chiefly "heavy" minerals, familiar in detrital sediments. The accessory minerals may be represented locally by a large number of different species, as elsewhere described in this book. Often, however, it is the fundamentally stable minerals which are found, *e.g.* ilmenite, tourmaline, zircon, garnet, rutile, anatase, titanite etc., though in some soils the yield of ordinarily uncommon minerals, *e.g.* olivine, augite, apatite, glaucophane etc., is very striking.

It is often impossible to anticipate with certainty either the character or the richness of the heavy mineral yield from a soil, even where the bedrock constituents are known. This is one of the reasons why petrographical investigation of soils proves such a fascinating study, since the presence of one or more minerals, not found in the underlying rocks or only occurring in rocks outcropping some distance away, immediately opens up interesting questions of provenance and, incidentally, of the natural history of the soils concerned.

The recognition of primary rock-forming minerals in soils depends largely on the degree of immaturity still retained. Obviously where such original species as felspar, hornblende (especially in cleavage fragments), mica, olivine etc., released from parent-rocks are still identifiable *per se* in the soil and, moreover, can be matched close at hand in solid rock or drift, then relationship between parent-rock and soil is at once unequivocally established. Actually such petrological relationship is likely to be more apparent in the subsoil zone than in the uppermost soil-layers, where radical changes tending to maturity may have been accomplished.

Mineral composition of the soil naturally tends to vary with that of the rocks immediately underlying it, except in those cases where the soil itself has not been formed *in situ*. Two contrasted influences are at work; either the soil rests on solid rock (with intervening sub-soil) or on drift. In the first case the nature of the rock exerts a definite influence, particularly in the accessory mineral composition of the soil. In the case of a drift soil, that influence is an entirely unknown quantity.

Plutonic, hypabyssal and volcanic igneous rocks each contribute their peculiar stable accessories in addition to their essential minerals during the process of surface-weathering. For instance, soils immediately overlying granite may be expected to yield accessory minerals, *ceteris paribus*, common to that rock. A volcanic rock rich in pyroxenes, for example, may be expected to give rise to a soil in which this family is represented by at least one or two species. Where metamorphic rocks are engendered, many minerals not usual to soils may be anticipated, *e.g.* sillimanite, kyanite, andalusite, in addition to the usual rock-forming minerals.

Sediments, whether of geological age or constituents of drift, tend to yield far less variety of detrital heavy minerals to soils than is the case with igneous rocks, owing to the fact that the soils in this case receive their components second-hand; only the stable minerals survive this re-constitution. On the other hand, a soil derived from a geologically youthful sediment may yield a prolific heavy mineral suite.

Where transported soils are involved, the mineral composition may be marked in its richness of species and their individual abundance or, by contrast, by impoverishment of species and infrequency of occurrence. In these types nothing goes by analogy; everything depends on proximity of source of supply of materials and on the nature of the soil environment in its ability to preserve original minerals or to determine their decomposition into some less definite product.

As affording some indication of the nature and variety of minerals found in soils, a list published by W. H. Fry of species determined during the course of considerable research by the U.S. Bureau of Soils into American deposits of this character may be quoted:—¹

Quartz	Glaucophane	Olivine	Tourmaline
Orthoclase	Enstatite	Epidote	Rutile
Microcline	Hypersthene	Zoisite	Ilmenite
Albite	Diopside	Piedmontite	Titanite
Oligoclase	Augite	Kaolinite	Fluorite
Andesine	Diallage	Apatite	Staurolite
Labradorite	Calcite	(Glass)	Corundum
Anorthite	Dolomite	Sericite	Sillimanite
Muscovite	Chlorite	Limonite	Kyanite
Phlogopite	Topaz	Hematite	Andalusite
Biotite	Axinite	Magnetite	Pyrophyllite
Actinolite	Serpentine	Garnet	
Hornblende	Iddingsite	Zircon	

¹ *Econ. Geol.*, 10, 1915, p. 292 and references cited.

It will be noted in this list that with only one or two exceptions, the minerals are familiar sedimentary rock species; no especially uncommon species have been identified, though in environments to which exceptional parent-rocks have contributed material, many other minerals could be imagined and have in point of fact been identified; this possibility is exemplified by soils in the neighbourhood of particular volcanic rocks or of outcropping metalliferous lodes etc.

To the above list may be added the following minerals noted from the author's observations of various British soils :—

Anatase	Glauconite	Marcasite	Monazite
Barite	Gypsum	Pyrite	Siderite
Chalcedony	Leucoxene	Pyrrhotite	Sphalerite

Exceptional and localised species further include :—

Mispickel	Galena	Malachite
Gold	Chrysoberyl	Azurite
Molybdenite	Cassiterite	Wolframite

J. Van Baren, in his researches on soils from the East Indian Archipelago,¹ found the following species in addition to many of those cited above :—

Amblygonite	Eucolite (?)	Copper	Vivianite
Chiaustolite	Graphite	Tremolite	[Asphalt]
Cordierite	Heulandite	Turquoise	[Volcanic Ash and Glass]

G. A. Neeb² records the occurrence of the following in Javanese sugar-cane soils :—

Bytownite	Leucite	Gibbsite
Sanidine	Goethite	

D. A. Carroll,³ as a result of detailed studies of some pod-sols, tropical, mallee and lateritic soils in Australia, was able to identify among many of the commoner minerals already mentioned the following :—

Pyroxene	Staurolite	Microperthite
Pleonaste	Chromite	

R. Hart⁴ notes an occurrence of palagonite in a soil from West Lothian, Scotland.

¹ *Communications Geol. Inst. Agric. Univ. Wageningen*, 1928, No. 14. (This is in English and is one of the best contributions to the detailed mineralogy of soils yet published.)

² "Identification of soils by mineralogical analyses." *Overdruk uit de Handelingen v/h 7^{de} Ned-Ind. Natuurwetenschappelijk Congres*, 1936, p. 695.

³ *Journ. Roy. Soc. Western Australia*, 20, 1933-34, p. 71.

⁴ *Journ. Agri. Sci.*, 19 1929, p. 802.

The above selections are sufficient to demonstrate the essentially varied character of the soil minerals, though it must be recognised that in so far as relative frequency of occurrence is concerned, there are striking contrasts, as is found in the case of ordinary sedimentary rocks; further, as already stated, in a majority of soils, particularly in what may be termed "sedimentary regions," only the common stable minerals may be expected to characterise the relevant superficial deposits.

It must be emphasised that mere lists of minerals seldom convey much in themselves, as is the case in other petrographical work. To be of any value at all in soil analysis, the various species reported must be subject to interpretation in terms of local geology or conditions of soil formation. Any deductions based on the prevalence of a particular mineral suite in a soil should always take into account the probable source of origin of that suite, and the special geochemical significance its presence implies (if any).

It is relevant to mention here that determination of many soil minerals is often rendered easier by employing refractive index (immersion) methods (p. 179), the favoured practice in the United States.

Mechanical Constitution of Soils.—This is an extremely important phase of soil investigation and its determination and interpretation are of necessity complementary to mineralogical studies. Fundamentally, the technique followed by pedologists in grading soil components is similar to that followed by others concerned with mechanical composition of sediments; the principles and practice involved, whether sieving, elutriation, sedimentation or otherwise, have been fully discussed in Chapter IV.

Herein it is relevant to call attention to certain departures from normal procedure which may be said to be customary in the technology now under consideration. In general, the principle of "falling velocities" (sedimentation) is followed by a majority of investigators in preference to elutriation. Bearing in mind the essentially fine character of the material itself, sieving is seldom employed excepting to reject adventitious stones and particles generally greater than 2 mm. in size. For this purpose an ordinary 2 mm. circular hole sieve is used.

It is further conventional to operate on soil samples which

have been deprived of their calcium carbonate and humus by preliminary process and dried in an oven at 100°C.-105°C. The proportions of these constituents are separately determined and will often be included in the ultimate analysis, which, according to what is known as the "Atterberg Scale," shows primarily the following fractions:—

Coarse Sand	...	2.0—0.2 mm.
Fine Sand	...	0.2—0.02 mm.
Silt	...	0.02—0.002 mm.
Clay	...	<0.002 mm.

Note the difference in classification employed compared with the P. G. H. Boswell convention (p. 85).

Problems of dispersion of soil particles are as difficult as with ordinary clay and fine mineral matter generally: the tendency to form aggregations is strong. The method laid down by the International Society of Soil Science is to boil the sample with 6 per cent. hydrogen peroxide to remove humus, then treat with 0.2 N hydrochloric acid and subsequent thorough washing to remove calcium carbonate and/or other bases intimately bound up with the clay substance and organic matter, then effecting the ultimate dispersion by shaking with 0.008 N sodium hydroxide.

In the sedimentation or subsidence method of making the mechanical analysis, the dried and previously dispersed soil sample is suspended in water of a chosen depth contained in a suitable glass vessel (ordinary measuring cylinders or gas jars are most used) and a settling time, *e.g.* 8, 12 or 24 hours, allowed depending on the nature of the sample under examination. At a given time there will be observed three more or less distinct zones of fluid charged with soil components: an upper or clay zone, a middle or clay-plus-silt zone, and a bottom zone composed essentially of sand, silt and clay (assuming the coarser fractions to be present).

Decantation of the upper clay zone is then carried out, water added to make up the original bulk, the whole suspension stirred and settlement again allowed to take place over a further (similar) time period. The process of decantation etc., is then repeated until, under ideal circumstances, no further "fines" remain in suspension. The soil-bearing fluid thus removed is

bulked, the clay filtered or otherwise segregated, dried and weighed.

G. W. Robinson has adapted this to the "pipette method" (officially adopted in 1926 by the Agricultural Education Association). This consists of determining "the concentration of a settling column of soil suspension after a given time at a given depth. For example, to determine the clay, a sample of suspension may be taken at 10 cm. from the surface after settling for 8 hours. The sampling is performed by means of a pipette introduced into the suspension and the concentration found, expressed as a percentage of the original concentration, gives the percentage of clay, *i.e.* of material having a settling-velocity of less than 10 cm. in 8 hours."¹

It will be apparent that where a number of analyses have to be carried out rapidly and with the minimum laboratory effort, the pipette method has much to commend it. On the other hand, in certain cases with relatively coarse samples elutriation is preferable, particularly where substantial amounts of fine and/or coarse sand are in evidence or where serial results are required between chosen grade-limits such as 0.02 mm. and 2 mm. The use of the Andrews Kinetic Elutriator (p. 98) is particularly apposite in the latter connexion on account of the comparative rapidity with which simultaneous segregation of chosen grades can be accomplished.

Mention must be made of exceptional cases where both elutriation and sedimentation methods of mechanical analysis of soils may break down. B. de C. Marchand has described instances of soils derived from basic igneous rocks (*e.g.* norite) containing high proportions of magnetite which, together with other heavy minerals, constitute 39 per cent. of the samples.² Similarly soils charged with minerals of micaceous habit are liable to present difficulties in accurate classification, while those refractory as regards reaction to dispersive agencies are well-known sources of trouble and potential error in results.

As previously explained (Chapter IV) the application of Stoke's law governs calculations in this matter. On this principle (that the limiting velocity of a particle falling freely in a

¹ *Op. cit.*, p. 14.

² *South African Journ. Sci.*, 18, 1922, p. 223.

fluid is proportionate to the square of its diameter) both coarse and fine particles can be defined in terms of settling-velocity; alternatively size or particle-diameter limits may be chosen, as is usually the case in petrographic work.

The limiting dimensions of coarse and fine sand, silt and clay as adopted by pedologists, have an advantage in that successive particle-size limits are at equal logarithmic intervals. G. W. Robinson prefers the use of settling-velocity or its logarithm to define the fractions, especially when dealing with the fine material; the following table is quoted from his work:—¹

Fraction.	Diameter Limits.	Settling Velocity (V).	Log. V.
Coarse Sand	2.0 — 0.2 mm.	347.6 cm./sec.	2.5412
Fine Sand	0.2 — 0.02 "	3.476 "	0.5412
Silt	0.02 — 0.002 "	0.03476 "	2.5412
Clay	<0.002 "	0.0003476 "	4.5412

Soil Colouring.—The natural colouring of certain soils invites observation as affording *inter alia* some indication of the character of the underlying rocks, though the explanation of particular colours is by no means always straightforward. Wet and dry soils cannot be compared from the point of view of colour, since there is obviously a lightening in tone as the moisture content decreases. Dried laboratory samples of different soil types are less easily distinguishable than field samples where colours are frequently vividly contrasted. The latter should, therefore, be used as a basis of investigation. Colour in soils may imply the influence of either organic or inorganic agencies, or both; it may be a secondary, even transient development in response to some biochemical process in operation in the soil environment.

Colloidal organic matter and colloidal clay are, as a rule, most influential in determining soil colour. Highly organic soils are usually dark in colour (black, dark grey or grey), owing to the products of anærobic decay of vegetable matter, often under swampy conditions. The effect of the organic content on colour is, however, more pronounced in sandy than in silty or clay soils.

¹ *Op cit.*, p. 15.

In soils which are not highly organic, colour is governed for the most part by the colloidal clay, though prevalence of individual unweathered minerals, such as hematite, limonite, glauconite, chlorite and magnetite, may sometimes be held responsible.

Yellow, buff or ochreous soils owe their colour generally to hydrated oxide of iron, *i.e.* finely divided limonite. Red soil is determined by prevalent red oxide of iron. Pale coloured soils, varying from white to dirty yellow, may be inferential of either calcareous components or sometimes of soils rich in aluminous silicates or phosphates; light-coloured soil is, however, sometimes entirely devoid of lime. In contrast are the brown, even dark grey soils of certain limestone regions which are predominantly calcareous. Vivid colouring, *e.g.* mauve, green or variegated streaks, is sometimes noted; chemical analysis usually shows this to be due to the presence of some highly coloured chemical salt, presumably in colloidal suspension.

A section exposing the complete sequence from bedrock to surface soil layers, whether relationship exists between the two or not, if just opened and examined in the fresh state, serves to reveal the passage of primary to secondary colouring matter through the successive zones. Such observations invariably prove instructive, especially when coupled with the results of petrological and chemical examination of the materials involved. Apart from mineral decomposition and the consequent generation of destabilisation products, the action of the meteoric water in its passage through the previous layers determines certain changes in soil constitution accompanied by corresponding changes in colouring matter, while the organic reactions set up by various plants similarly find their colour expression.

Much data on colour of soils, as still obtains with certain uncommon sedimentary rocks, remains to be collected by comprehensive chemical, petrological and physical investigations into a variety of chosen and dissimilar soil-types. The nature of a particular soil colour may be surmised, but the actual cause is often surprising on detailed investigation. Soil-colour changes are often abrupt and vary with depth from the surface, vegetation, degree of moisture and so on; but whether abrupt

or gradual, it is part of the petrologist's work to ascertain the reason.

From a qualitative standpoint there is, however, a difficulty in recording soil colour unless some standard scale of colours is chosen as arbiter by an international body. Modern practice appears to be to attempt to match a particular soil colour with a recognised colour chart (*e.g.* Ridgway) or with composite colours obtained by combining various standard colours in known proportions. In this connexion the work of J. G. Hutton is interesting and should be referred to by the reader.¹

In the author's opinion there is abundant scope for profitable research on this question, particularly in any attempt to explain soil colour in terms of combined ecological and geological data investigated in specific environments, where these are known factors.

The Function of Sedimentary Petrology in Soil Investigations.—As has been shown in this chapter much has already been done towards clarifying the mineral composition of soils by appeal to petrographic methods conceived in their fullest and most modern sense. Looking ahead, we perceive still a large vista of research in which the petrologist can assist in unravelling problems of soil constitution. His work must naturally fall into two categories, analytical and deductive.

From the purely analytical standpoint, the sedimentary petrologist's contribution is abundantly clear. His part is essentially that of the mineralogy of soils which to-day is an entirely different conception from that of even a few years ago. C. E. Marshall has summed up the situation in a paragraph which we cannot do better than quote here :—

“The soil mineralogy of the future has many tasks before it. It has to trace the detailed relationships between chemical constitution and physical properties in the whole group of the clays. It has to formulate in its own terms the processes of rock weathering and of soil formation. Finally, it has to hand over to the soil physicist workable concepts which he can use in his studies of soil structure. Therefore, it seems likely that

¹ *Proc. 1st Int. Congr. Soil Sci.*, 4, 1928, p. 164.

mineralogy is destined to be of increasing importance in soil science, and one can see already that in this new field of the colloidal minerals, soil science will eventually repay some of its debt to mineralogy.”¹

On the theoretical side, conclusions drawn from laboratory data will inevitably follow lines of reasoning adopted by the sedimentary petrologist in his many and varied stratigraphical problems. Some of his functions in this particular philosophy may be indicated as follows :—

- (1) Elucidation of the genesis of soils from their mineral constituents.
- (2) Influence on soil structure of prominent minerals.
- (3) Distinction between sedentary and transported soils; also between drift and bed-rock soils.
- (4) Correlation and differentiation of soils in a given province.
- (5) Relationship of particular soils to local geological conditions and peculiar rock types.
- (6) Determination of the means by which certain needs of vegetable life are met in so far as these relate to inorganic (mineral) components of soils.
- (7) Significance of soil colouring.
- (8) Interpretation of mechanical analysis of soils according to the principles recognised in the case of other sedimentary deposits.
- (9) The application of soil mineralogy to problems of definition and classification.
- (10) Elucidation of fundamental changes taking place in soil environments under different climatic conditions where such changes are directly or indirectly attributable to the mechanism of destabilisation of mineral constituents.

¹ “ Soil Science and Mineralogy.” *Soil Sci. Soc. Amer., Proc.* 1, 1937, p. 29.

The following is a selected bibliography of modern literature having reference to the particular phases of pedology discussed in this chapter:—

NOTE.—The student should consult the following periodicals and special publications concerned with soil science:—

- Empire Journal of Experimental Agriculture.* (Oxford University Press).
Industrial and Engineering Chemistry. (Amer. Chem. Soc.).
Journal of Agricultural Science. (Cambridge University Press).
Journal of the American Society of Agronomy. (Geneva, U.S.A.).
Soil Research, Bodenkundliche Forschungen, Recherches sur le Sol. (Internat. Soc. Soil Sci., Berlin N4, Invalidenstrasse 42).
Soil Science. (Williams and Wilkins, Baltimore, U.S.A.).
Technical Communications. (Imperial Bureau of Soil Science, Harpenden, Herts, England).
U.S. Dept. of Agriculture (Bureau of Soils) Publications. (Washington, D.C. U.S.A.).
Zeitschrift für Pflanzenernährung, Düngung und Bodenkunde. (Verlag Chemie, Berlin).

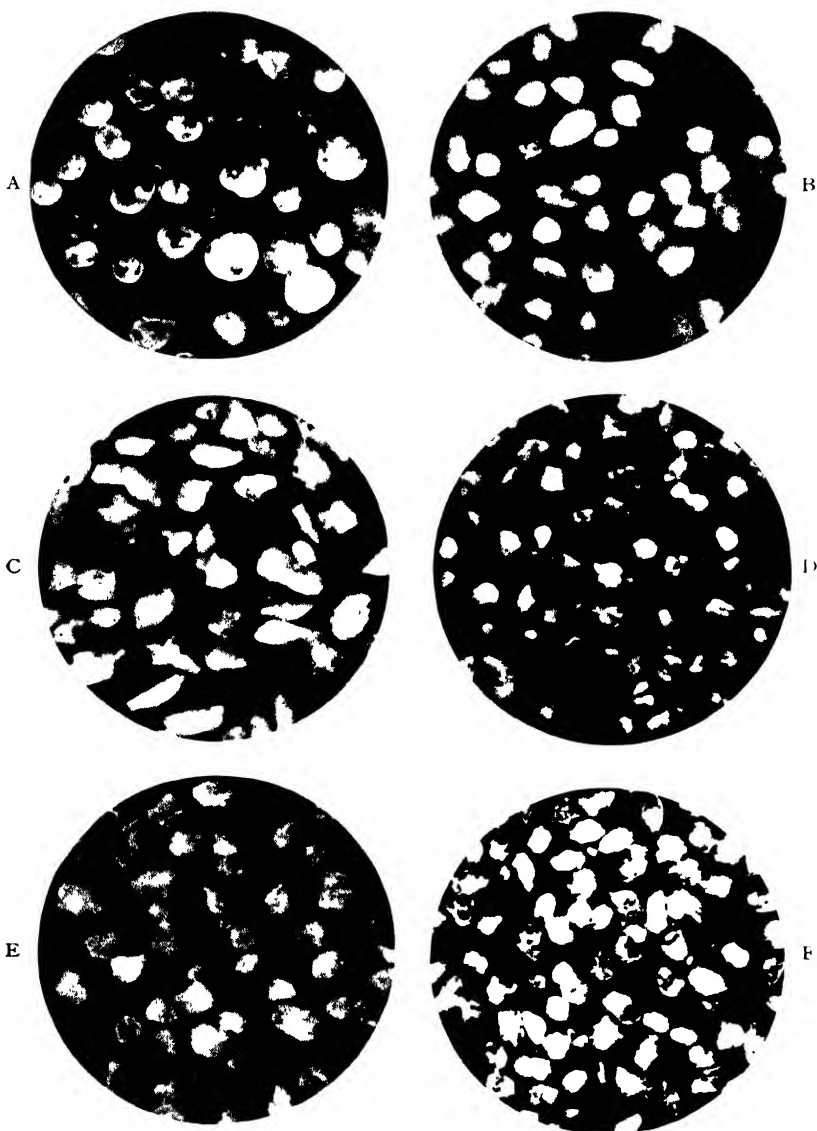
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A-F AGGREGATES FROM VARIOUS ASPHALTIC LIMESTONES.

- A Boeton, Dutch East Indies [x 16]
 B Scafa, Italy. [x 16.]
 C Sicily [x 30]
 D St. Jean de Maruejols, Gard, France. [x 19]
 E Pyrimont, Seyssel, France [x 16]
 F Val de Travers, Neuchatel, Switzerland. [x 19]

To face page 541

PLATE 48

ERRATA —For illustration C read D, and vice versa

CHAPTER XV.

APPLIED SEDIMENTARY PETROLOGY.

Asphalt Industry (Building Construction)—Building Technology—Cement Technology—Ceramics—Criminology—Fillers — Glass Technology—Highway Construction—Medicine (Industrial Maladies)—Refractories—Water Supplies.

ACADEMICALLY, as we have seen, sedimentary petrology is now a firmly established branch of geological science and its functions are widely appreciated wherever sediments constitute the object of investigations. We have further learned in this book to what extent certain major industries have made use of this knowledge, more particularly where stratigraphical problems demand positive solution for important economic motives. The influence of the petroleum industry on rapid evolution of this petrology has already been stressed. No less important to-day are many other professional and commercial callings wherein the principles of the subject and the practice of its tenets play an important, though possibly less generally realised, part in the march of progress.

It is the intention in this chapter briefly to review some of the less widely known applications of the subject in the hope that this will serve to give the reader an idea of its almost unlimited scope in everyday life, also to stimulate a breaking of fresh ground wherever petrographic methods may seem to have legitimate and profitable entry. No attempt is made to cover every ramification; only the more important modern adaptations can find space here. A short bibliography of relevant references at the end of each section will, however, enable the reader to follow up in appropriate detail such applications as may interest him.

Asphalt Industry (Building Construction). — The increasing use of mastic asphalt in water-proofing buildings, especially those constructed of reinforced concrete, by the

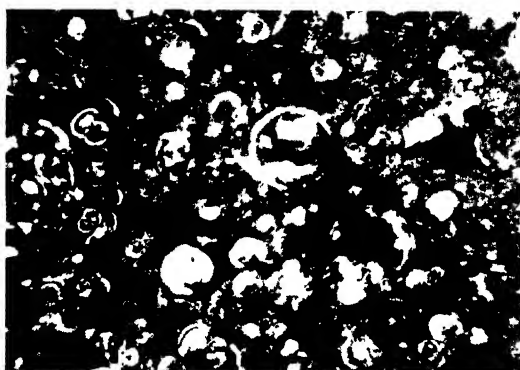
laying of horizontal and vertical dampcourses, roofs, skirtings, fillets etc., has created in this country a highly important and specialised industry which may be said originally to have had its beginnings abroad.

Mastic asphalt is essentially a mechanical mixture of a rock aggregate and a specially selected asphalt cement in such proportions as will give a product which, when heated, can be worked with a float into the desired position, thereafter setting into a compact, voidless, impervious mass.

In the latter part of the nineteenth century, much of the building mastic asphalt used in this country was made exclusively from foreign natural rock asphalt, *i.e.* naturally impregnated bituminous limestone, mined or quarried in the Bassin de Seyssel, Departments of Ain and Haute Savoie, France and elsewhere. The word "Seyssel" thus came to be the hallmark of a well recognised product and a household word among the older architects, surveyors and engineers. It was customary then, as it still is in some cases to-day, to specify simply "Seyssel" asphalt, meaning by that a natural rock asphalt mastic, the aggregate of which was derived solely from the Seyssel district. The fact that no commercial deposits of bituminous limestone occur in Britain supported the belief that "Seyssel" asphalt was indeed the best possible material.

Actually other parts of France, *e.g.* Department of Gard, also other countries such as Italy, Sicily, Germany and Switzerland, produce high grade bituminous limestones suitable for manufacturing good quality natural rock asphalt mastics. Such limestones in a majority of cases have no geological and certainly no geographical connections with "Seyssel," so that technically considered the significance of that particular name is more apparent than real.

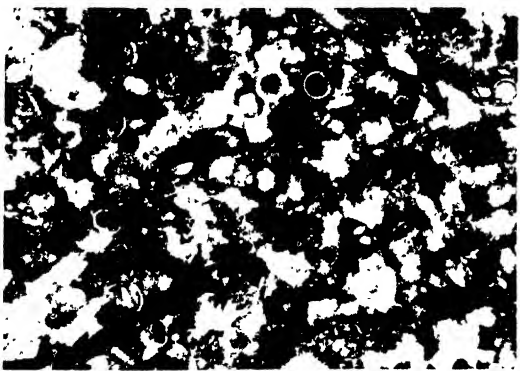
With the rapid progress of petroleum technology, especially in connection with refining of petroleum, there were gradually placed on the market various standard grades of asphaltic bitumen used successfully not only for fluxing the bitumen in naturally impregnated rocks and in fluxing native bitumen such as Trinidad Lake Asphalt, but also capable of direct mechanical admixture with crushed limestone powder to form mastic asphalt products. Thus were the so-called "synthetic" mastics introduced; these had a material com-



B



C



A, B, C ASPHALTIC LIMESTONES (Natural Rock Asphalts).

A. Bonten, Dutch East Indies (*F. ramulifera*) [X 9]

B. Scala, Italy [X 24]

C. Sicily [X 35]

To face page 542.

PLATE 40.

mercial advantage over natural rock asphalt mastics in that the former could be manufactured in this country without importing foreign rock and could, therefore, be produced much more cheaply. The development of these "synthetic" mastics was enormous, especially after the war, so much so that from the standpoint of commercial production and use, natural rock asphalt mastics to a large extent gave place to them, though technical opinion was and still is sharply divided on the question of relative merits of the two types, especially concerning durability with age. Certainly, the natural rock products are more expensive and are still claimed by their protagonists to be far superior to mastics compounded of British limestone, asphaltic bitumen or any other type of asphalt cement.¹ However, we are not here concerned with technical controversy on this matter but rather with the illegitimate use of "synthetic" mastic where contracts have definitely called for natural rock asphalt mastics.

For a long time there was no generally recognised method of analysing these mastics which would give unequivocal evidence as to the source of origin of the aggregate. Chemists grappled with the problem from the standpoint of the bitumen involved, but soon found themselves up against serious difficulties in recovering it in unchanged form from the product, quite apart from the impossibility of isolating inherent bitumen in the natural rock (where used) from that which had been added as a fluxing medium. The geologists' attack lagged still farther behind and consequently for some years substitution of "synthetic" for natural rock asphalt mastic, where practised, went unchallenged. All that has since been changed by the building up of a technique which is now highly specialised and, in the hands of experts, gives the desired evidence in practically all cases.

In the first place, each of the well-known natural rock asphalts from recognised sources in France, Germany, Italy and Switzerland has been exhaustively studied as regards the actual limestones involved, their micro-organisms, inorganic mineral components (including heavy mineral suites), inherent structures, manner and degree of impregnation by the bitumen

¹ C. M. Watkins and C. M. Gough, "The Use of Asphalt Mastic for Roofing." *Dept. Sci. Ind. Res., Building Research Spec. Rep.* 25, 1937.

and, in the crushed state, as regards characteristic shapes of the particles involved. In the author's laboratory, many hundreds of reference microscope slides depicting each of the above features have been accumulated over a period of years and are used for comparison with aggregates segregated from mastic asphalts under test. Such a collection is a *sine qua non* to correct interpretation of evidence derived from direct tests. On the chemical side, the inherent bitumen of these rocks has been extracted and studied in great detail by modern methods, involving not only standard physical tests of characteristics, but also chemical determinations, such as asphaltene content, saponification and acid values, also colorimetric analyses, both of the bitumen itself and its segregated asphaltenes, coupled with relevant fluorescence tests of both bitumen and natural rock.¹ All this evidence aids classification, comparison and differentiation of the several rock asphalts now commercially exploited and serves together with petrological data to fix identity of a particular rock in the raw state.

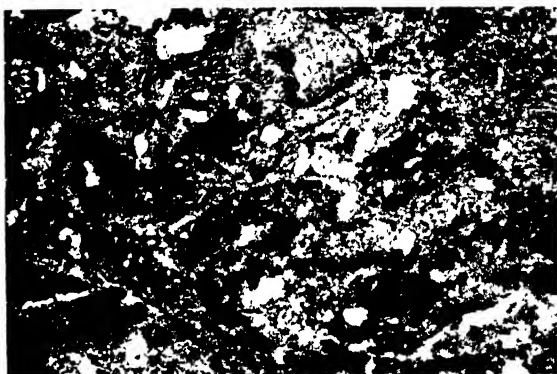
In the case of "synthetic" mastic asphalt, in this country it is customary to use for the most part Carboniferous Limestone from such areas as the Mendip Hills, the Peak district of Derbyshire, North Wales, Northumberland etc. This rock, in its crushed state, is used as aggregate for the mastic concerned (except in special cases where sand, slate dust etc. may be incorporated for certain reasons) and is readily recoverable in its original state for petrological examination, the mode of attack on such material, with a view to its identification, following normal petrographic technique for the study of incoherent sedimentary rocks. Again, a large and representative collection of microscope preparations must be available for reference, involving thin sections of the original solid rocks, carefully localised as to every main centre of supply, slides of powders resulting from crushing them, slides of heavy mineral residues extracted from such powders, slides specially selected to show micro-organisms characteristic of particular developments and so on. Intimate stratigraphical knowledge of these Carboniferous Limestone occurrences is also essential, as is the case with other limestones occasionally employed for the purpose

¹ L. J. Chalk, "The Recovery of Bitumen." *Journ. Soc. Chem. Ind.*, 56, 1937, p. 156.

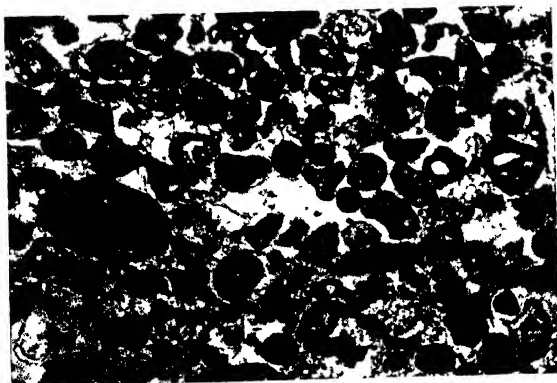
A



B



C



A, B, C. ASPHALTIC LIMESTONES (Natural Rock Asphalts)

A. St. Jean de Maruéjols, Gard, France. [X 17]

B. Montrotier, Seyssel, France. [X 17.]

C. Puyrion, Seyssel, France [X 21]

and, what is equally important, where such rocks are mineralised, *e.g.* Northumberland, Cumberland, Derbyshire and elsewhere, the nature, extent and main areas of development of the resultant ore-bodies must be known.

Space forbids discussion of the various collective "indices" of the different British limestone powders used in the asphalt industry to-day, but suffice it to say that Carboniferous Limestone of one area is by no means uniform in petrographical or palæontological characteristics with limestone of similar age in another. For instance, different developments vary in the amount and character of crystalline calcite present; in development of dolomite; in the larger organic components the fragmentary remains of which are frequently recognisable in the crushed rock; in the nature of the foraminifera present; in the nature of the oolite grains where prevalent; in the nature and amount of inorganic matter such as silica and iron. The same applies to the heavy mineral constituents which, as segregated by modern methods, are generally much more prolific than is usually imagined for calcareous rocks.

The best known example of a limestone "indicator" is the fluorite characteristic of the Carboniferous Limestone of the Matlock district, Derbyshire, whence is derived considerable quantities of powder used in manufacture of "synthetic" mastic asphalt. This mineral is so prolific that even the smallest amount of aggregate recovered from a sample of mastic involving this particular powder will reveal its presence. Further, it is not simply a question of identifying fluorite *per se*, but of observing its special physical and optical characteristics which distinguish it even from other fluorite developments. Obviously, as this *Derbyshire* type of fluorite is unknown both in other British limestone developments and in any of the European natural rock asphalts employed, its presence *ipso facto* points to the source of origin of the aggregate and where contamination or adulteration of a natural rock asphalt has occurred, the fact is immediately betrayed by observation of the blended "indices" of both rocks involved. It is further to be noted that this type of fluorite is absent from the components often employed in mastic asphalt apart from the filler, namely the various "grits" used as coarse aggregate and particularly from the inherent heavy mineral residue

of Trinidad Lake Asphalt, so frequently a constituent of the asphalt cement used, but which itself carries a distinctive and easily recognised mineral suite. (See *Pl.* 51 c.)

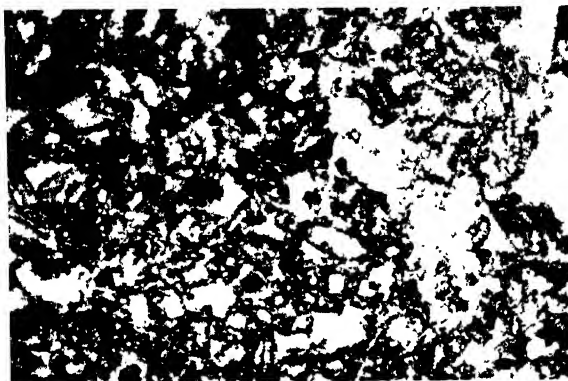
Two other examples may be quoted of British limestone developments, characterised on the one hand by doubly terminated quartz crystals of remarkable definition and individuality and on the other by barite possessing distinctive traits. Thus, the evidence in every case is not far to seek in the hands of expert investigators. In fact, in some instances, it is even possible to estimate approximately the amount of contamination by British limestone which has affected an otherwise pure natural rock asphalt mastic.

A pertinent means of differentiating between naturally and artificially impregnated limestone particles is by close microscopical study of the associated brown matter, *i.e.* bitumen. In the case of naturally impregnated rocks the bitumen penetrates the finest interstices of grains and particularly the innermost walls of cells, chambers or other organic (fossil) structures. This is seldom, if ever, achieved in the case of a purely mechanical admixture of hard, crystalline limestone filler and asphaltic bitumen whatever its character. In the latter case, staining is superficial, being a survival of the film made to coat the particle during the mixing process. With naturally impregnated limestone, the rock is in nearly all cases softer in character, much less crystalline and far more permeable, hence it lends itself initially to intimate and thorough penetration by the original mother-fluid, *viz.* crude petroleum, which gave rise to the bitumen as now observed.

Petrological studies of the mineral matter in native asphalts, *e.g.* Trinidad Lake Asphalt, Cuban Asphalt, are conclusive in the evidence their characteristic heavy mineral suites provide as a means of their identification; frequently where chemical and physical methods fail to give decisive results, such evidence is quite convincing. Much yet remains to be done in extending these methods to various native asphalts containing mineral matter and as yet relatively little known in this country.

Finally, there is the fact that recovery of the total bitumen from mastic asphalt products is now a much more exact process and that, in certain cases, comprehensive testing of the bitu-

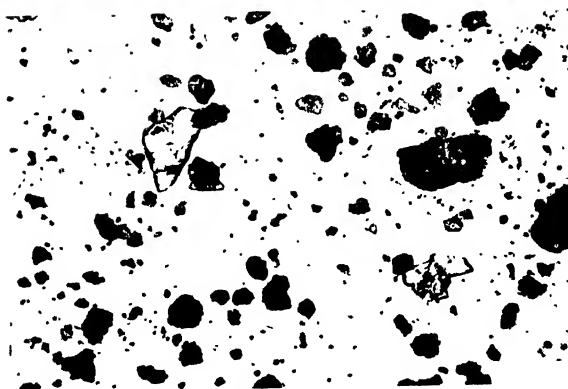
A



B



C



A, B. ASPHALTIC LIMESTONES (Natural Rock Asphalts)

C. CONTAMINATED ROCK ASPHALT POWDER.

A. Val de Travers, Neuchatel, Switzerland [x 33]

B. Vorwohle, Hanover, Germany [x 30.]

C. Natural Rock Asphalt Powder contaminated with British Carboniferous Limestone (Note Fluorite grains.) [x 51.]

men so obtained furnishes invaluable supporting evidence of the presence or absence of naturally impregnated asphaltic limestone.¹ (See also under Highway Construction, p. 573.)

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Building Technology.²—Sedimentary petrography has many direct applications in modern building construction concerned as it is with such varied types of natural and artificial stones.

Natural stone, whether utilised as primary constructional material or purely as decorative facing or for other purposes, should never be selected haphazardly, but rather with due regard for its durability with age, for the facilities which it offers for fashioning into set designs and, where employed externally, with particular reference to its weathering tendencies, especially in urban and industrial areas. The invaluable researches of the Building Research Station (Department of Scientific and Industrial Research) have over an extended period done much to educate public opinion as to the reasons why some building stones are superior to others in service. For instance, the problem of weathering of natural building stones has been tackled on a scientific basis and in the understanding of the chief factors involved, chemical, geological and physical influences have all been studied, their effects correlated and pertinent deductions drawn therefrom.

The weathering of sandstones, limestones (including magnesian limestones) is dependent on inherent natural defects in

¹ L. J. Chalk, *op. cit.*

² See also under Asphalt Industry (Building Construction), p. 541, Cement Technology, p. 557.

the selected rocks, such as soft beds, vents and shakes, on unfavourable structures, on bad workmanship in selecting and fashioning the stone, on the effect of atmospheric pollution in congested cities and industrial areas, on temperature changes, moisture, frost, action of inherent soluble salts (florescence) and in some cases on organic agents of decay (bacteria, lichens etc.). The application of the microscope to the study of many selected building rock-types by means of thin sections, especially resin-impregnated bodies (p. 42), is a technique which we owe largely to the Station and the assessment of macro- and micro-porosity by this means, to mention only one phase of such research, has proved to be of vital importance in interpreting the phenomena observed.

In our own country sedimentary rocks figure conspicuously both in ancient and modern buildings. Chief among these building stones are undoubtedly the famous Portland limestones from the Isle of Portland, Dorset, which include oolitic limestone, locally known as "Roach"; the fine-grained variety is used specially for plinths, bridges and abutments, the "cavernous" (shelly rock) type being employed particularly for sea-walls, dock-yards and harbour construction. The "Whitbed" is the chief oolitic type from which block-stone is prepared; it is essentially this bed which furnishes typical Portland Stone. Other well-defined beds include the "Base Bed" oolitic limestone and a compact crystalline type, "Perrycot," which can be cut into large rectangular slabs and fashioned for decorative work such as wall-linings, columns and pilasters. These varieties of Portland Stone are macroscopically conspicuously differentiated, but when studied by means of thin sections under the microscope their inherent characteristics and structural differences are soon apparent.

Somewhat similar to the oolitic Portland limestones of Dorset are the famous "Freestone" and oolitic limestones of the Great Oolite age, as developed in the quarries and underground workings near Bath, Somerset.

Apart from these Jurassic building stones, certain sedimentary rocks from other stratigraphical horizons are widely employed in the building industry for their high quality, uniform texture, pleasing appearance and durability in service. Among these may be cited the Old Red Sandstone of Lanark-

shire and Dumbartonshire, the Carboniferous Limestone of the Mendips and the Peak District, the Pennant Sandstone of the Coal Measures of the Bristol District and South Wales, the magnesian limestones (Permian) of the Mansfield District, Nottinghamshire, the fine-grained micaceous sandstone known as the "St. Bees Head Freestone" of Cumberland, the Ketton Stone (Lincolnshire Limestone) from the Inferior Oolite of Rutland, also limestone of similar age known as the "Ancaster Freestone" from Lincolnshire. This list can be considerably extended, but the examples have been selected not only because of their importance in the building industry, but also because representative samples of each of these will form an excellent basis of study for comparative data for the student who is interested in the application of sedimentary rocks to building construction.

Next in the category of natural rocks employed as building and ornamental stones come slates. These, however, as ultimate products of dynamic metamorphism of fine argillaceous matter, are necessarily excluded from a treatise on sedimentary rocks *per se*, but no description of modern building materials would be complete without at least passing reference being made to this ancient and important industry. Apart from its primary function as roofing and dampcoursing material, slate to-day finds extensive use for monumental purposes such as surfacing for flat roofs, pavements, brewery tanks, aquarium construction, laboratory balance room equipment etc., the noted areas of production being Blennau Ffestiniog, North Wales and Delabole, Cornwall.

Of latter years considerable technical research has been conducted for the purpose of extending the use of slate, for improving its appearance (artificial colouring) and for utilising slate-waste.¹ Part of this research has involved a technique which includes methods well known to petrographers. Mineral composition, mechanical analysis of dust, determination of particle size, classification of superfine material etc., are among some of the data sought and achieved by petrologists who have taken part in these investigations; it will readily be appreciated to what valuable use the microscope can be put in determining some of these properties of slate and its products.

¹ See section on Fillers, p. 566.

In sharp petrological contrast to these slates are certain sedimentary rocks, "Tilestones," "Flagstones," used for roofing purposes. The famous "Stonesfield Slate" (Great Oolite series) is a good example of the type of rock involved. This "slate" has been employed to great picturesque advantage in many Cotteswold buildings, as those familiar with that country are well aware. The rock is essentially a thinly bedded sandy limestone, flagstone rather than true slate, since it possesses no cleavage which is the fundamental characteristic of real slates. "Cotteswold Slate," as it is known, has been worked for centuries at various places, especially in the North Cotteswolds and is now principally exploited from Salperton, Naunton, Eyford Hill etc. The principal "slate" bed is known as the "Pendle" and a microscopical study of this and associated types soon reveals the structure and composition which together determine the characteristic weathering of these rocks.

Passing from consolidated to incoherent sediments employed as building materials, it is common knowledge that practically every type of sedimentary deposit, whether of mechanical, organic or chemical origin (p. 360) finds some economic use in constructional work. Gravel, sand, clay, marl, limestone, gypsum, to mention a few fundamental raw materials, enter into the manufacture of the chief artificial (including many forms of decorative) products incorporated in modern buildings.

The utilisation of these materials gives rise to an enormous number of manipulative problems; each has its own particular technique, wherein chemists, petrologists and physicists may pool their specialised knowledge to ensure that only proper raw materials are selected for the particular purpose in view and, further, to control scientifically such process of manufacture as may be necessary to the ultimate product. It is, in fact, the sum total of this knowledge concerned with so many variable raw materials and the still greater number of artificial products made therefrom which constitutes the wider subject of building technology as we know it to-day, constituting a branch of applied science of comparatively recent growth, but one which none the less is making extremely rapid strides.

The following is a list of the principal raw materials used in the building industry and the products derived from one or more of them :—

RAW MATERIALS.	PRODUCTS.
Gravel	Concrete.
Sand	Cement and lime mortar, concrete, plaster, bricks, sand-lime bricks, tiles.
Clay	Bricks, tiles, ceramic products, fire-bricks, refractories.
Marl	Cement.
Limestone	Lime, hydraulic lime, hydrated lime, Portland cement, lime putty, plaster.
Gypsum	Plaster.

In the investigation of these raw materials the technique follows closely the various methods laid down in this book for determining physical constants. In the case of gravel aggregates for concrete, it is desirable that the rock (flint, chert etc.), whether in natural state or crushed, shall be hard, strong and durable, clean and free from authigenic matter. Deleterious materials such as coal, ash, breeze, slag and porous components must be excluded. Much the same applies to the fine aggregate (sand), where it is desirable that all silt or clayey matter should be absent. Both coarse and fine aggregates must comply with conventional gradings, depending on the design of the particular concrete mix laid down.

Sand for plaster, bricks, tiles etc. is chosen largely with regard to local resources, suitable composition and grading and the tests which are necessary to determine suitability have been previously described.

With clays used for brick and tile making, investigations include colour, hardness, behaviour on drying, manner in which the dry clay breaks, mechanical analysis, specific gravity, degree of plasticity achieved with known water-content, tests on weathered material, pugging tests, cutting tests etc.; the chemical composition must be known and firing trials on the raw clay carried out to give information as to how it will stand up to the normal process of burning.

Selection of suitable calcareous rocks for the manufacture of cement is largely a matter of local resources and utilising either an extremely pure form of the carbonates, such as chalk, together with such clay as may be best suited for blending;

alternatively, by employing less pure limestones or marls which in some cases can be burned direct. Similarly, selection of pure raw material for calcium sulphate plasters is a matter depending to a large extent on the mineralogical purity, freedom from adventitious rock fragments and so on and the tests necessary to determine the favourable qualities of such material are again in part within the province of the sedimentary petrologist.

One obstacle to narrowing the gap between technical progress and empirical trade custom, for instance in the employment of mechanically formed aggregates such as ballast gravel, sand etc., has been the lack of a generally agreed nomenclature for the diverse materials known and used in the building industry. Tradition in this industry, as in many others, dies hard and it has taken the combined influence of government departments, standardisation committees and mandatory codes of practice to remove prejudice to scientific procedure; in other words, to make building science a real live factor in its everyday commercial applications. In the author's experience it is highly desirable that some standardised nomenclature should, in fact, be achieved so that builder and scientist are both talking the same language. In an effort to clarify the position concerning aggregates, the author some time ago published a number of definitions which have since constituted a basis of discussion in appropriate places.¹ No apology is needed for inclusion of these definitions here, some of which will be long familiar to the sedimentary petrologist.

AGGREGATE. — (1) Inert incoherent material composed of gravel, sand, crushed natural rock, or suitable crushed synthetic products, comprising slag, clinker, or combinations thereof, with which specific bonding media are incorporated to form mortar, concrete, asphalt, tar macadam etc. (H.B.M.)

(2) All the inert solid or vesicular materials from natural sources or artificially fused which, mixed with tar, asphalt or asphaltic cement, form a road surfacing. (Tech. Dict. Road Terms, Perm. Inter. Assoc. Road Congresses.)

AGGREGATE (FINE).—The fine inert constituents of a rock or other mineral mixture retained on a standard sieve (not

¹ "The Nomenclature of Aggregates." Ballast, Sand and Allied Trades Assoc., *Bull.* 2, July, 1930, p. 5.

larger than 6 mm. in size). (Tech. Dict. Road Terms, Perm. Inter. Assoc. Road Congresses.)

AGGREGATE (COARSE).—The coarse inert constituents of a rock or other mineral mixture, retained on a standard sieve (over 5 or 6 mm. in size). (Tech. Dict. Road Terms, Perm. Inter. Assoc. Road Congresses.)

BALLAST. — (1) Small stones mixed with grit, sand and clayey materials in such proportions as to produce, when consolidated, a coherent layer, in which the major portion of the particles is retained on a standard sieve having 4 square meshes to the lineal inch (England and U.S.A.). (Tech. Dict. Road Terms, Perm. Inter. Assoc. Road Congresses.)

(2) Ballast means (a) gravel, shingle, ashes, or clinker, or (b) any material commonly known in the Building and Engineering Trades as ballast, stone chippings, granite chippings or hard core of brick, stone, stone ware or concrete, or (c) any similar material commonly known and used in the said trades as an aggregate for constructional work. (Weights and Measures Act, 1936.)

(3) The term "ballast" is taken as meaning all mixtures of stone and sand, of which the voids in the stones are filled with sand. (Original definition, Ballast, Sand and Allied Trades Association.)

BOULDER.—Naturally eroded and isolated derivative of a consolidated rock. (H.B.M.) In England usually applied to detached rounded rock fragments larger than egg-size pebbles. In U.S.A. is restricted to detached rock masses having a minimum major dimension of 256 mm. (10 inches). (Based on C. K. Wentworth's classification.)

CHIPPINGS.—(1) Rock fragments produced by mechanical crushing process, essentially of angular shape and ranging in size from 1 to $\frac{1}{8}$ in. (H.B.M.) (See also B.S.S. 63—1928.)

(2) Angular stone fragments usually about $\frac{1}{4}$ to $\frac{3}{4}$ in. in size. (Tech. Dict. Road Terms, Perm. Inter. Assoc. Road Congresses.)

CLAY (1).—A natural deposit of extremely fine texture usually plastic when wet and hard when dry and consisting substantially of disintegrated rock particles less than 0.01 mm. (0.0004 in.) in diameter. (Based on P. G. H. Boswell's classification.)

(2) That fraction of so-called "fine earth" in which the particles are less than 0.002 mm. (Atterberg Scale, Inter. Soc. Soil Science, 1927.)

COBBLE.—A naturally eroded derivative of consolidated rock, of similar character to "boulder" (*q.v.*), having a minimum major dimension of 64 mm. ($2\frac{1}{2}$ in.) and maximum dimension of 256 mm. (10 in.). (Based on C. K. Wentworth classification.)

FILLER.¹—(1) Finely ground mineral matter or other inert substance commonly employed as a constituent of the matrix in certain constructional materials, *e.g.* asphalt. (H.B.M.) *Note.*—Fillers for certain road-surfacing materials (excluding Portland Cement or Blast-Furnace Cement) must all pass an 85 B.S. sieve, and not more than 15 per cent. must be retained on a 200-mesh B.S. Sieve. (See B.S.S. 594, 595—1935.)

(2) An inert, finely divided powder employed to give body to a bituminous binder or to fill the voids of a sand. The portion impalpably fine is called "flour." (Tech. Dict. Road Terms, Perm. Inter. Assoc. Road Congresses.)

(3) Relatively fine material mixed with the aggregate for the purpose of reducing the voids. (Not applicable U.S.A.) (Tech. Dict. Road Terms, Perm. Inter. Assoc. Road Congresses.)

FLOUR.—The impalpably fine portion of a filler. (Tech. Dict. Road Terms, Perm. Inter. Assoc. Road Congresses.)

GAUGE.—Term applied to standard groups of sizes into which broken stone and chippings are divided. British Standard for road stones and chippings are $2\frac{1}{2}$ in., 2 in., $1\frac{1}{2}$ in., for chippings (*q.v.*) 1 in., $\frac{3}{4}$ in., $\frac{1}{2}$ in., $\frac{3}{8}$ in., $\frac{1}{4}$ in., $\frac{1}{8}$ in. (B.S.S. 63—1928 and 1939.) *NOTE.*—The term "gauge" has been superseded by "standard nominal sizes" (1939).

GRANULES.—A loose detrital sediment in which the grade size from 2 mm. (0.08 in.) to 4 mm. (0.16 in.) predominates. (Based on C. K. Wentworth's classification.)

GRAVEL.—(1) Naturally eroded derivatives of consolidated rock or loose detritus in which the minimum grade size is 2 mm. (0.08 in.). (Based on P. G. H. Boswell's classification.)

(2) Colloquially applied in the building trade to specific concrete aggregates which include pebbles and sand.

¹ See section on Fillers, p. 566.

(3) Small stones, usually waterworn, sometimes mixed with finer materials, occurring in natural deposits. (Tech. Dict. Road Terms, Perm. Inter. Assoc. Road Congresses.)

GRIT.—(1) A sandstone composed of angular particles. (H.B.M.)

(2) A term frequently employed in the trade for aggregate of graded particles (*e.g.* flint) ranging from $\frac{3}{16}$ in. to $\frac{1}{8}$ in. or less. (H.B.M.)

(3) Fine sharp gravel or coarse sand. (Tech. Dict. Road Terms, Perm. Inter. Assoc. Road Congresses.)

HOGGIN.—Small stones, mixed with grit, sand and clayey materials in such proportions as to produce, when consolidated, a coherent layer in which the major portion of the particles passes a standard sieve having 4 square meshes to the lineal inch and is retained on a standard sieve having 10 square meshes to the lineal inch. This last condition only obtains in the United States of America. (Tech. Dict. Road Terms, Perm. Inter. Assoc. Road Congresses.)

PEBBLE.—(1) A naturally eroded derivative of consolidated rock with greatest length not less than 4 mm. ($\frac{1}{8}$ in.) or more than 64 mm. ($2\frac{1}{2}$ in.). (Based on C. K. Wentworth's classification.)

(2) Rock particles of diameter greater than 2 mm. (P. G. H. Boswell's classification.)

RUBBLE.—An accumulation of angular rock and/or artificial stone fragments of entirely ungraded character and heterogeneous composition. (H.B.M.)

SAND.—A loose detrital sediment composed substantially of quartz grains (SiO_2) in which the grade size 0.1 mm. (0.004 in.) to 2 mm. (0.08 in.) predominates. (Based on P. G. H. Boswell's classification.)

SAND, COARSE.—A loose detrital sediment composed substantially of quartz grains (SiO_2) in which the upper limit is 2 mm. (0.08 in.) and the lower limit 0.5 mm. (0.02 in.). (Based on P. G. H. Boswell's classification.)

SAND, FINE.—A loose detrital sediment composed substantially of quartz grains (SiO_2) in which the upper limit is 0.1 mm. (0.004 in.) and the lower limit is 0.05 mm. (0.002 in.). (Based on P. G. H. Boswell's classification.)

SAND, MEDIUM.—A loose detrital sediment composed sub-

stantially of quartz grains (SiO_2) in which the upper limit is 0.5 mm. (0.02 in.) and the lower limit is 0.25 mm. (0.01 in.). (Based on P. G. H. Boswell's classification.)

SHINGLE.—(1) A term applied to water-worn, shore-line gravel (*q.v.*). Substantially free from sand (*q.v.*). (H.B.M.)

(2) Loose detritus of coarser grades than those of gravel, *e.g.* having a majority of the pebbles of a larger size than a walnut. (A. Holmes, *Nomenclature of Petrology.*)

N.B.—The definition (2) in part overlaps that of "cobble" (*q.v.*).

(3) The term "shingle" is taken as meaning all stones retained on $\frac{1}{8}$ in. mesh. (B.S.A.T.A. Bulletin, No. 1, 1936, p. 10.)

SILT.—A loose detrital sediment in which the grade size from 0.01 mm. (0.0004 in.) to 0.1 mm. (0.004 in.) predominates. (Based on P. G. H. Boswell's classification.)

N.B.—The term is often applied to a "sandy clay." For purposes of testing aggregates for suitability for use in concrete it is usual to regard that portion of the aggregate which can be washed through a 200 mesh B.S. sieve (aperture 0.076 mm.) as "clay and silt." (A.S.T.M., D. 136-28.)

SIZE.—A subdivision of the term "gauge" (*q.v.*) as above defined. (See B.S.S. 63—1928 and 1939.)

For the rest, modern building research covers an ever-widening field of investigation in which in certain directions petrographic methods are invoked with great technical advantage. It is after all the translation of results of such research in terms of everyday economic procedure in building construction and maintenance that constitutes the essential role of the technologist in this great industry and anything that sedimentary petrography can contribute to the understanding of building materials, whether in the raw or synthesised form, is of the greatest possible economic value.

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Cement Technology.—It is convenient to group under the general title "cement" a number of important artificially prepared substances widely used in building and engineering constructional work, either *per se* or as constituents of cement mortars, lime-sand mortars, plasters, concrete etc. concerning which there has evolved over the last few decades a highly specialised and ramified technology.

Taking as a starting point the principal naturally occurring rock-types utilised as raw materials in the preparation of these various "cements," we may note the following:—

Chalk.
Clay.
Diatomite.
Dolomite.
Gypsum.
Limestone.
Magnesite.
Marl.
Mud.
Pozzolana (Pozzuoli, Italy and elsewhere).
Santorin Earth (Santorin, Greece).
Trass (volcanic tuff, Eifel).

Each of the above, as naturally occurring rock, is capable of petrological study along conventional lines to assist determination of impurities and interpretation of chemical analyses prior to selection and use. The following is a list of the chief products manufactured from one or more of the above materials :—

Aluminous cement (*e.g.* Ciment Fondu).

Gypsum cement (plaster of Paris).

Hydrated lime (slaked lime).

Hydraulic lime (*e.g.* containing up to 25 per cent. silica and alumina).

Keene's cement (*e.g.* calcined gypsum mixed with cream of tartar and borax and re-calcined).

Lime (quicklime).

Magnesium lime.

Natural hydraulic cement (*e.g.* Roman cement).

Portland blast-furnace cement (*e.g.* Portland cement plus crushed, blast-furnace slag).

Portland cement.

Pozzolanas (natural and artificial).

Rapid hardening cement (*e.g.* Ferrocrete).

These various cements, together with different aggregates such as sand, gravel etc., enter into the design of the ultimate products known to engineers and others as mortars, plasters, concrete and so on. Thus microscopical investigations in this technology concern the natural raw materials, the cements manufactured therefrom and also the products into which they enter.

In so far as petrological studies of cementing materials *per se* are concerned, these have been prosecuted by specialists all over the world for a long time past but, although admittedly presenting extremely complex subjects, it cannot be said even now that any real degree of finality has been reached in all cases. The separation of individual constituents of certain cements still presents almost insoluble problems from the standpoint of their identification as definite crystalline compounds and equally in cases where artificially produced silicates and other compounds unite in forms which defy identification by normal microscopical methods.

The constitution of Portland cement clinker is a case in point. In the first place a special technique must necessarily be employed for production of the thin sections to be investigated. Water obviously cannot be used as a lubricant and

glycerin or white spirit is frequently substituted. The question of friability of such clinker frequently has to be faced when some form of impregnation with synthetic resin or other suitable substitute must be adopted before grinding (see p. 42). It is also possible to study the sections of cement clinker by metallurgical methods using polished and etched surfaces which are examined with reflected light.

Apart from examining thin sections, auxiliary chemical, optical and physical tests have frequently to be carried out in specially synthesised compounds for purposes of comparison and only the experienced cement microscopist with intimate knowledge of the crystallography and optical properties of such artificially prepared silicates etc., can reasonably hope to interpret such materials successfully. In this connection, staining has proved of great utility, the use of dyes such as anthrapurpurin, patent blue, methylene blue, safranin and eosin proving extremely helpful.

For the examination of set cements, F. M. Lea and C. D. Desch¹ have recommended the use of naphthol green B (the ferrous sodium salt of nitroso- β -naphthol monosulphonic acid) which stains hydrated lime compounds green with the exception that large crystals of calcium hydroxide do not absorb sufficient dye to colour them properly. The method involved is to gauge the cement with 20 per cent. aqueous solution of the dye and to immerse the pat in the same solution until ready for sectioning. When such a thin section is examined under the microscope, the unhydrated cement particles are seen to be birefringent and slightly brown in colour. The groundmass of hydrated cement is green and isotropic, while large crystals of calcium hydroxide are birefringent and colourless, smaller crystals being green.

It was the initial difficulties in identifying the components in Portland cement clinker and related products which led A. E. Törnebohm to coin the terms "alite," "belite," "celite" and "felite" for such constituents as were regularly identified but, perforce, remained unnamed. Although these terms have, to a large extent, been discarded as unscientific and therefore worthless, they still appear in the literature, unfortunately often with different meanings.

¹ "Chemistry of Cement and Concrete." (Arnold, London), 1935.

Actually, recent studies of Portland cement clinker indicate that the essential compounds entering into its composition are silicates, aluminates and ferrates. Of the silicates, calcium metasilicate (wollastonite), dicalcium silicate and tricalcium silicate are the most important; aluminates are chiefly calcium derivatives, as also are the ferrates. In addition, calcium and aluminium hydroxides may be present, together with more or less free silica.

These substances, providing they are properly isolated or, as is more generally the case, specially prepared for the purpose, are individually susceptible to microscopical examination and to precise optical studies. Such properties as refractive index, birefringence, sign and optic axial angle may be determined with a considerable degree of accuracy; these properties serve not only to confirm the crystal systems to which such compounds belong, but also as important factors in identification of and distinction between various silicates, aluminates etc.

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Ceramics.—Fundamentally the ceramic industry is concerned with the "plastic art" of mixing, moulding or shaping, then burning, clay in the manufacture of pottery, porcelain, earthenware, terra cotta and similar products. Both in technology and commercial activities, relationship with the refractories industry (p. 589) is very close, while many of the commonest building materials are fabricated from raw substances and so processed as to bring them well within the category of ceramic products.

The aid which sedimentary petrography affords in the technology of ceramic products is two-fold; investigation of raw materials and the microscopy of synthetic bodies produced therefrom. The former demands the ordinary relevant petrographic methods, but microscopical investigation of fired pro-

ducts is a different matter altogether, involving specialist knowledge of processes, conditions of firing, mineral inversions and recognition by one means or another of complex artificial silicates etc. entering into their constitution.

The raw materials employed in this industry are many and varied, comprising not only specially selected natural potters' clays and minerals but also fluxes, stains for glazing, pigments etc. Of the natural rocks and minerals employed, the following list comprises the most important; an indication is also given of the uses to which such raw materials are normally put.

SUBSTANCE.	PURPOSE.
Ball clay.	Porcelain, earthenware.
Bauxite.	Source of alumina.
Ceramic talc (steatite).	Wall-tile bodies.
China clay.	White china-ware, sanitary goods, electrical porcelain.
China stone.	Porcelain, earthenware.
Felspar.	Flux.
Fireclay.	Sanitary tiles, saggars, cylinder liners, pavors etc.
Flint.	Source of amorphous silica.
Fluorspar.	Flux.
Kaolin.	Porcelain.
Kyanite (calcined).	High-temperature bodies, sparking plugs etc.
Magnesite.	Source of magnesia.
Mullite (synthetic from sillimanite).	High-temperature bodies.
Nepheline-syenite	Flux.
Pegmatite.	Source of felspar.
Pyrophyllite.	Wall-tile bodies.
Quartz.	Source of silica.
Sillimanite (calcined).	High-temperature bodies, sparking plugs etc., added to clay and kaolin to reduce shrinkage, increase breaking strength, extension of sintering range.
Spodumene.	Pottery bodies.
Titanium oxide.	Whitening agent.
Whiting (prepared from chalk).	China-ware.

Petrological examination of raw materials has for its chief end determination of mineral composition as an aid to interpreting chemical analyses; it is particularly valuable in recognising impurities or deleterious compounds considered from the standpoints of the firing cycle and the ultimate product.

In investigation of the fired bodies a number of vital characteristics may be determined with the use of the microscope, aided by such optical, spectrographical and/or X-ray methods as may be appropriate to each case. Among the characteristics commonly sought are the following :—

- (1) Uniformity or otherwise of grain size (texture).
- (2) Preponderant particle size (or sizes).
- (3) Mass structure (mutually interferent crystals; matted fibres; punctate structure; "porphyritic structure"; "granular structure" etc.).
- (4) Artificial mineral composition.
- (5) Degree of conversion or inversion achieved.
- (6) Presence or absence of glass.

There is no short-cut method of approach to problems of artificial mineral constitution of ceramic bodies. Each case has to be considered on its own merits and with some previous knowledge of the components employed, fluxes used, process and firing cycle. Examination is made both of thin sections where practicable and powdered samples. Whenever the microscope is employed, this implies extra high power magnification and illumination which are essential to this work. Precise refractive index determinations on the powder or on separate components segregated by heavy mineral, centrifugal or other methods are essential when diagnosing these artificial minerals and a table such as that given by A. N. Winchell¹ is invaluable for running down the species present.

Spectrographic and X-ray methods are obviously specialised technique, but when adopted they follow generally the procedure given in Chapter VI. The preparation of photomicrographs of highly magnified components of these ceramic bodies is extremely valuable in comparing properties of similar products, also as a visual record of the habits and characteristics of the many artificial crystalline inorganic substances which constitute pottery and porcelain.

The student who first attempts a study of artificial minerals will find that the best way of starting is to acquire some thin

¹ "Microscopic Characters of Artificial Inorganic Solid Substances or Artificial Minerals." (Chapman and Hall, London), 1931, p. 346.

sections, also mounts of loose mineral grains, of such substances as calcined andalusite, calcined kyanite, calcined sillimanite, mullite, tridymite, cristobalite etc. These should be studied intensively as regards their optical properties and direct determinations should be made of their refractive indices and specific gravities. The series should be extended to include similar artificial minerals (in some cases it is advisable to procure naturally occurring examples where possible) from different sources and products. Variations in characteristics will thus be noted and can be recorded as a basis of reference. Gradually as new bodies are examined the components can be isolated for comparable studies and thus a collection of microscopic objects built up which will be found invaluable for comparative purposes.

Many ceramic bodies are remarkably fine in grain and the production of sufficiently thin sections demands considerable skill; without such sections, however, microscopic work is abortive. It should be added that as full a chemical analysis as possible of each of the above materials forming the initial collection is of the greatest importance in aiding microscopical observations. Ability to interpret such analysis in terms of the artificial mineral composition is equally a valuable asset.

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Criminology.—The microscope is employed nowadays almost universally in examination of fibres, sand, dust, bullets, documents, banknotes, stains etc. Generally any first class instrument capable of giving magnifications up to 500 diameters is employed, but special forms have been devised to meet particular requirements of criminal investigation (technical) departments.

Document microscopes normally have no stage and carry the objective and eyepiece on an arm which can be extended directly over the book or paper to be examined; magnifications ranging from 48 to 72 diameters are usually employed for this purpose. An eyepiece micrometer for the measurement of size of printed characters or width of ink lines is usually incorporated in the instrument.

Binocular stereoscopic microscopes find special application in the study of coins, bullets and cartridge cases, although with the latter what are known as "comparison microscopes" give information of greater value. With this apparatus, images from two microscopes are made to appear side by side in one field of view, thus enabling minute differences in two objects to be readily distinguished. In the hands of an expert, an empty cartridge case will reveal the actual weapon from which a bullet was fired and the markings on the case caused by the striker, breech face, bullet head, extractor or ejector should prove to be distinctive.¹

Petrographic methods in general and the petrological microscope in particular have now taken their place in investigations of crime and in specialist hands have in more than one criminal charge played an important part in building up evidence against the suspected person. For instance, it is sometimes desirable to ascertain and prove, if possible by comparison with known material of definite origin, the source

¹ A. Lucas, "Forensic Chemistry and Scientific Criminal Investigation." (Arnold, London), 1935.

of mud, sand, dust or other inorganic matter adhering to clothes, boots, skin, hair etc., and in such cases the most intensive researches often on minute quantities of material are prosecuted. Similarly, refuse, garbage, ashes from fire-grates, boilers and the like are subject to exhaustive tests which may and frequently do include microscopical examination and optical determination of any mineral particles isolated therefrom.

To the lay mind, mud, sand, soil, powder, dust, stains or other matter of that character, scraped off boots or clothing, even walking sticks, appears by its nature and usually meagre quantity to be most unpromising material on which indications, if not actual proof, of a person's movements may be based, but in expert hands, this information, coupled with other evidence, can be fruitful of astonishing results. It is not always a question of heavy minerals, which may or may not be recoverable, depending on the nature and quantity of material available, though as every petrographer knows it is surprising in some cases how little sediment is necessary to yield readily identifiable mineral species, if not suite, which not only betrays geological source of origin but, cautiously interpreted, helps to narrow down a possible area from which it has been derived. To quote a simple example, in some parts of the Lower Greensand outcrop, the heavy mineral suite is prolific and an amount which would comfortably adhere to a person's boots between the heel and sole would be quite sufficient, in expert hands, to betray the fact that those boots had made contact with that particular deposit.

Apart from heavy minerals, the examination of the particles themselves for grain-size, shape, authigenic coating, colour, peculiar surface features etc., are all taken into account in any exhaustive microscopical examination for the purpose in view. When it is realised that such familiar domestic commodities as new bath sponges, certain abrasive soaps, scouring powders, washing soda, old-fashioned egg-timers, carpets, rugs, mats and oil cloth, can often be made to yield identifiable heavy minerals, it is clear that even the most calculating criminal has to be doubly wary if he would avoid the consequences and implications of such "dust" detection.

Naturally, this kind of evidence presents certain difficulties

when given in a court of law, owing to the fact that it is necessarily extremely technical and highly specialised knowledge is required, not only in handling the data, but in adapting it to the circumstances of the case and more particularly in making it understandable to the court. On the other hand, it is seldom that learned counsel, supported by acknowledged expert witnesses, fails to present such evidence in a manner which is both convincing and comprehensible, even though a shattering cross-examination may serve to demonstrate conflicting expert opinions and the proverbial inexactitude of geological science.

From the standpoint of actually presenting such evidence, however, it is becoming increasingly common in legal work to take photomicrographs wherever possible of such material as above described and there is no doubt whatever that this course is preferable to staging demonstrations in court with a complicated petrological microscope. In this way, characteristic features can be explained to a jury far more easily by the aid of enlarged photographs constituting a series of "exhibits" than by asking each one in turn to look through a microscope, an instrument with which the great majority of jurymen and women is totally unfamiliar and, moreover, incapable of forming any sound judgment by mere scrutiny of sediment particles.

Fillers.¹—From a strictly technical standpoint the essential function of a filler is to occupy voids in an otherwise balanced aggregate incorporated with a fluid or semi-fluid matrix. Alternatively fillers are employed when properly dispersed to give homogeneity and a degree of solidarity to what are initially plastic substances. Industrially filler is looked upon as a reinforcement and as a cheapening agent. It is usually an inert substance, *i.e.* one which has no chemical reaction with the medium with which it is mixed. A property common to practically all fillers employed in industry is the extremely fine state of division of the constituent particles; in a majority of cases filler is essentially -200 mesh material containing a proportion of particles of unit micron size or less.

Fillers employed in manufacturing processes to-day vary greatly in mineral composition. In many cases they are by-products of rock-quarrying operations which had for long been

¹ For technical definitions of the term "filler" see p. 554.

regarded as unremunerative crusher-run "dust," a waste material for which there was no apparent outlet. With the growth of certain key industries however, such as plastics, rubber, asphalt, paint etc., the demand for suitable inert fillers has been increasingly great since the war, so that practically every producer of fine "dust" derived from both natural or artificial materials has been at pains to ascertain to what extent these presumably waste-substances could be utilised in other industries. Considerable research has therefore been carried out on a host of raw materials and their successful employment as fillers in the several industries concerned has been one of the most remarkable testimonies to the value of modern industrial research.

The following list of materials employed as fillers in various industries to-day is not intended to be exhaustive; in fact it is doubtful whether any list could be regarded as final in view of the fact that so many new additions are being made from time to time, not only of natural rock powders, but also of the by-products of certain industries concerned with synthetic substances. Among the commonest fillers employed are the following :—

Ashes (" Fine stuff ").	Gypsum.
Barite.	Hydrated lime.
Bauxite.	Limestone dust.
Bentonite.	Micro-anhydrite.
Carbon black.	Micro-asbestos.
Cement.	Micro-dolomite.
China clay.	Micro-limestone.
Clay (dried and pulverised).	Micro-talc.
Clinker (ground).	Precipitated chalk.
Diatomite.	Rubber, disintegrated (rubber waste).
Flue dust.	Slate dust.
French chalk.	Sulphur.
Fuller's earth.	Tripoli powder.
Granite dust.	Whiting.
Ground glass.	

It will be observed that most of the above substances are essentially naturally-occurring rocks or minerals for the most part artificially rendered to a fine state of division. In nearly every case microscopical examination will reveal not only purity of composition or otherwise, but also average particle size and shape, the two latter among the most important pro-

perties used to determine suitability of a specific filler for a particular manufacturing process.

The industries most closely concerned with utilisation of fillers and the chief purposes served by the incorporation of such materials may be summarised as follows :—

INDUSTRY.	PURPOSE.
Anti-corrosive compounds.	Stabiliser; hardening in service.
Asphalt.	Void filling; hardening; durability.
Cement.	Void filling in asphalt etc.
Chemical.	Anti-caking agents for deliquescent crystals; support for catalysts.
Cosmetics.	Absorbing agent; perfume and pigment carrier.
Electrical.	Stabiliser in bituminous battery box and cable compounds etc.
Gramophone records	Homogeneity of mixture; smoothness of sound reproduction.
Linoleum.	Stabiliser; resistance to wear.
Paint.	Inert extender; flattening agent.
Paper.	Loading agent.
Pharmaceutical preparations.	Absorbing agent.
Plastics.	Stabiliser of moulded articles.
Printing inks.	Control of consistency; pigment carrier
Rubber.	Stabiliser; hardening of product; resistance to abrasion.
Soap.	Absorbing agent; abrasive cleansing etc.

Many substances which normally satisfy industrial requirements as fillers are also extensively employed as clarifiers, filter-aids, detergents, decolorising agents etc.; among these may be specifically mentioned bentonite, carbon black, diatomite and Fuller's earth.

Since the majority of fillers is essentially incoherent, artificially produced powders, the mother-substances of which are in most cases naturally occurring rocks or minerals, it is clear that their investigation and classification, especially as regards mineralogical and mechanical composition, will depend largely on modern petrographic methods.

For most practical purposes, however, the following is a list of the tests normally carried out on fillers in the author's laboratories :—

- (1) Specific gravity.
- (2) Weight per cubic foot.
- (3) Hygroscopic moisture.

- (4) Chemical composition.
- (5) Petrological examination.
- (6) Classification of principal particle sizes by elutriation or sedimentation.
- (7) Void calculation.
- (8) Computation of surface area of constituent particles where practicable (sq. m./kg.).
- (9) Practical trials with the fluid or matrix (with or without associated aggregate) with which the filler is to be incorporated.

Methods of carrying out the above determinations are sufficiently described elsewhere in this volume and reiteration is unnecessary here. Suffice it to say that in the building up of the technology of fillers, sedimentary petrography and, in particular, the methods which pursuit of this science invokes, has played an important part and is still materially influencing the trend of research in widening the field of utility of finely ground mineral substances.

In view of the number of different materials involved, the appended bibliography contains references grouped under specific substance headings.

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Glass Technology.—The well-known memoir on "Sands and Rocks Used in Glass-Making" by P. G. H. Boswell¹ some years ago pointed out the way in which intensive petrological study of certain sediments, in particular sands, could reveal their suitability or otherwise for this purpose and since that time a great deal of comparable work has been carried out on raw materials by glass technologists, who are now fully alive to the uses and ramifications of the petrological microscope.

Raw materials include various high grade silica sands, siliceous rocks containing alumina and potash, pure sandstones and quartzites, ground flint, certain quartz schists, vein quartz, feldspars, aplite, kaolin and steatite. The checking by petrographic methods of one or more of these components of the "batch," *i.e.* the mixture which, on fusion, results in the glass product, is admittedly only a small part of a much more comprehensive technology embracing chemical and physical problems of considerable complexity. But it is none the less an essential factor in assessing the quality and behaviour of such raw materials.

In so far as sand as a raw material is concerned, P. G. H. Boswell lays it down that "The ideal sand for the best glass-making is one with 100 per cent. silica and composed of angular grains all of the same size, and of the grade known as medium or fine sand. Such a perfect sand has not at present been discovered, but the ideal is approached by a few sands, including those of Fontainebleau in France (99·7 per cent. silica), Lippe in Germany (99·8 per cent. silica), and Berkeley Springs in the U.S.A. (99·65 per cent. silica)."²

Generally, the most objectionable impurities in sands are iron-oxide, limonite or clay. Heavy minerals such as rutile, anatase, zircon, garnet, monazite, if present in any quantity, are also undesirable as they are prone to resist fusion and occur as visible blemishes in the finished glass. In the case of a crushed quartzite, vein quartz etc., one of the objections to the use of such material is the amount of fine dust involved, which unless eliminated and thus more or less wasted, upsets the critical grading limits to which manufacturers normally work.

¹ Longmans Green, London, 1918.

² *Op cit.*, p. 48.

Examination of raw materials of the "batch" involves both routine tests of periodical consignments of sands etc., whether of British or foreign origin and a check on their conformity or otherwise to works' specification. Similar work is carried out on such new raw materials as may from time to time be offered. The methods employed involve essentially determination of chemical composition, mineral composition and particularly mechanical analysis; if the results of these are satisfactory, practical tests on such raw material blended as may be necessary with other known components are carried out on a semi-large-scale prior to translating the formula to commercial dimensions.

Apart from the use of sedimentary rocks in the manufacture of glass, it should be noted that many igneous rocks are also employed for this purpose, especially on the continent, *e.g.* basalt, trachyte, phonolite, while American practice frequently favours the use of felspar, china clay and lepidolite, especially those reasonably free from iron oxide which are successfully employed in the production of colourless glass.

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Journal of the American Ceramic Society.
Bureau of Standards Journal of Research.
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Glastechnische Berichte.
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Keramische Bundschau.

Highway Construction. — British Standard Specification No. 63—1939, "Sizes of Road Stone and Chippings," includes among others the following sedimentary rocks used according to varying circumstances as roadstones; it is to be

noted that the "trade names" are in many cases misleading, as the specification is at pains to show:—

PETROLOGICAL.	TRADE GROUPS.
Arkose.	Gritstone.
Breccia.	do.
Chert.	Flint.
Conglomerate.	Gritstone.
Dolomite.	Limestone.
Flint.	Flint.
Ganister.	Quartzite.
Greywacke.	Gritstone.
Grit.	do.
Limestone.	Limestone.
Quartzite.	Quartzite.
Quartzitic sandstone.	do.
Recrystallised quartzite.	do.
Sandstone.	Gritstone.

The application of the petrological microscope to a study of selected types as above is now standard technical procedure and its practical import has been well demonstrated by B. H. Knight.¹ In particular, the structures of these rocks are significant, also mineral composition, nature of cementing materials and degree of decomposition, as affecting durability in service. Generally speaking, with few exceptions, sedimentary rocks are definitely inferior to igneous rocks for first class road construction, *i.e.* where traffic is heavy; but in many cases, such as country roads and comparatively lightly trafficked highways not involving any heavy industrial areas, carefully selected hard limestone, quartzite or flint may prove quite a satisfactory aggregate for either water-bound surfacings or with asphaltic bitumen or coal-tar binders.

In this latter connection, certain Pre-Cambrian and Ordovician quartzites, also Carboniferous Limestones, give good results in practice, due mainly to their possessing a greater degree of consolidation, relative absence of lamination, stratification and intricate fissuring and consequent toughness under load, than geologically younger rocks of their type. For example, the Pre-Cambrian Appin quartzite, Kentallen, Argyllshire, N.B., the Ordovician Stiper quartzite, Pontesbury, Shropshire and the Carboniferous Limestone from areas

¹ "Road Aggregates, their Uses and Testing." (Arnold, London), 1935.

such as the Mendip Hills, Peak District, North Wales, to quote a few prominent examples, provide eminently satisfactory road metal. Quartzite pebbles, either in their natural state or crushed, from the Bunter Pebble Beds of the Trias, frequently make good aggregates, also form successful binders with asphaltic bitumen and sand for superimposition of non-skid, rolled asphalt wearing surface. Alternatively, such crushed material, like crushed flint, is used satisfactorily in some cases both for "blinding" sprayed bitumen or tar and for precoated chippings.

Jurassic and Cretaceous limestones are usually too soft for use as aggregates except in quite local circumstances, crushed flint from the extensive gravel developments of the home counties being the more favoured, not only for use as macadam, but particularly for concrete. Sandstones, more particularly Palæozoic types, are in some cases sufficiently hard to be used as road aggregates, but they find more common employment in the fashioning of kerbstones and setts, for which, incidentally, much Carboniferous Limestone is used in the localities in which it is chiefly developed.

The advantage of petrological investigation of these sedimentary rock-types is not only as a means of making a selection between good and indifferent stone, but is especially valuable in aiding interpretation of results of physical and mechanical tests made on road surfacing materials, particularly in cases of failure.

Petrographical identification of certain sedimentary rocks was standardised for the first time in B.S.S. 598—1936, on "Sampling and Examination of Bituminous Road Mixtures," and although procedure and description as therein laid down have since been severely criticised and are now under revision, recognition of the need for determining more precisely the aggregate in an asphalt road carpet constituted an important step in progress in the technology.

In rolled asphalt composed of stone, sand and cement (B.S.S. 594, 595—1935), it is now essential to examine petrologically such components, either as original individual bulk samples or as recovered from the carpet itself. The stone is determined by means of thin sections, the sand and cement being examined in the usual manner. In this way, not only

may the components be checked against definite provisions of the specifications, but precise sources of origin, where these are stipulated in the contract, can be ascertained and certified accordingly. In examining the finished carpet (wearing course), grouping of components into -200, 200-8 and +8 (B.S. sieves) grades, forms the basis of initial separation and examination of the total aggregate. In cases where Trinidad Lake Asphalt is used, it is necessary to go further with the fine material (-200) and, apart from other tests, examine the heavy mineral residue for species which confirm evidence of its inclusion in the asphalt cement; any heavy mineral residue due to the sand or other components tends to be of coarser grade and can generally be readily eliminated and distinguished.

In specifications calling for use of "Compressed Rock Asphalt" (B.S.S. 348-1935), it is desirable to know whether "approved natural limestone asphalt rock, naturally impregnated with not less than 8 per cent. nor more than 13 per cent. of bitumen" has been employed in the manufacture of the asphalt. The raw rock, frequently both in lump form and in powder, is submitted and examined petrologically for nature and source of origin, while tests of the finished asphalt, subsequent to laying, proceed on much the same lines. The underlying motive of such investigations is, of course, detection of adulteration with unimpregnated limestone, comparable in most respects with that technique described for the examination of building mastic asphalt based on natural rock asphalt (p. 543).

A much favoured form of road-surfacing, using mastic asphalt, is that in which the mastic is prepared at the contractor's works in the usual way, compounded either of ordinary limestone aggregate or of natural rock asphalt aggregate with a given asphalt cement, the blocks being subsequently reheated on site with the incorporation of igneous or calcareous chippings (B.S.S. 596 and 597-1935). Here, again, the problem is usually to determine whether the materials specified by the engineer have indeed been exclusively used throughout the manufacture of the carpet as laid. If a sample of the carpet alone is submitted, it is not always possible to be certain that the specification has been rigidly adhered to in all respects, although adulteration *per se* can soon be detected. The latter, if proved, may lead to a very exhaustive examination of the cir-

cumstances and of materials involved in the whole contract, even some time after it has been completed. It is, however, advantageous to carry out such tests collaterally with the laying of the asphalt, in which case samples of the raw materials used, both sedimentary and igneous rocks and equally the asphalt cement, are examined.

From the above remarks, it will readily be appreciated that applications of sedimentary petrography to the technology of modern highway construction are both many and varied and the science is becoming of ever-increasing importance as it rightly should, for its evidence on the often complicated problem of design of road foundation and surfacing materials best suited to local conditions and available expenditure.

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 Highways and Bridges.
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 Journal of the Society of Chemical Industry.
 Road Abstracts (compiled monthly by the D.S.I.R. and Ministry of Transport).
 Roads and Road Construction.
 Strade.
 Strasse.

The following British Standard Specifications are relevant :—

- No. 63 — 1939. Sizes of Road Stone and Chippings.
- No. 347 — 1928. Asphalt Macadam.
- No. 433 — 1931. Cold Asphalt Macadam.
- No. 434 — 1935. Asphaltic Bitumen Road Emulsion.
- No. 510 — 1933. Single-Coat Asphalt (Cold Process).
- No. 511 — 1933. Two-Coat Asphalt (Cold Process).
- No. 594 — 1935. Rolled Asphalt (Fluxed Lake Asphalt and Asphaltic Bitumen) Hot Process.
- No. 595 — 1935. Rolled Asphalt (Fluxed Natural Asphalt and Asphaltic Bitumen) Hot Process.
- No. 596 — 1935. Mastic Asphalt Surfacing (Fluxed Lake Asphalt and Asphaltic Bitumen) Hot Process.
- No. 597 — 1935. Mastic Asphalt Surfacing (Fluxed Natural Asphalt and Asphaltic Bitumen) Hot Process.
- No. 598 — 1936. Sampling and Examination of Bituminous Road Mixtures.
- No. 802 — 1938. Tarmacadam. Part 1.—Tar macadam (Granite, Limestone and Slag Aggregate). Part 2.—The Surfacing of Roads with Tar Macadam.
- No. 812 — 1938. Sampling and Testing of Mineral Aggregates, Sands and Fillers.

Medicine (Industrial Maladies).—The chief avenue of medical research open to the collaboration of the sedimentary petrologist is that leading to elucidation of causes of industrial pulmonary diseases. The action of dust (conceived in its broadest sense) on the human lungs has been keenly debated ever since it was recognised that prolonged contact of the human being in confined spaces with certain forms of dust produced a form of phthisis which in many cases has proved fatal. The subject has been one of international investigation and keen controversy between the various scientific authorities concerned and even to-day they are by no means agreed on the causes and, more particularly, the mechanisms of the various types of incapacitating fibrosis whose toll of human life has been so tragic.

Foremost in this field of research is silicosis, for long believed to be due exclusively to the action of finely powdered *uncombined* silica, the particles being of the order of 2μ and less in size. That such fibrosis is not exclusively due to free silica has since been proved by the fact that asbestos dust is also a potent cause of fibroid phthisis (asbestosis) and in this case the silica is in a combined state as a hydrated magnesium silicate.

Dusts in any form and from whatever substance derived may under certain conditions be deleterious to the health of the operative who is obliged to work in what is unquestionably a

most unhealthy atmosphere. It is only of comparatively late years that legislation has empowered authorities to compel the exclusion of dust as far as possible in factories where processes tend to promote such unhygienic conditions. It is true, of course, that not all dusts are injurious to human life or perhaps it would be better to say that in so far as diagnosis of pulmonary diseases is concerned, certain types of dust have so far escaped suspicion in that no case of fibrosis has been directly traced to their incidence. This does not imply, however, that with further research it will not ultimately be found that many dusts at present not suspect will have to be placed on the black list to ensure protection of human life. "The dictum is true that *all* dusts in excessive amount must be injurious, if not to the lungs, then to the upper air passages, causing atrophy of the mucous membrane with loss of vibrissæ round the margin of the nose due to the catarrhal discharge set up."¹

The petrologist's contribution to investigation of industrial dusts as conducive to phthisis is essentially that of (a) examination of the various rocks believed to be capable of causing silicosis or asbestosis; (b) examination of inorganic mineral matter recovered from silicotic or otherwise infected lungs of diseased persons; (c) reconstruction on a chemical and mineralogical basis of the mechanism by which inorganic mineral matter in a fine state of division can attack lung tissue, react chemically with lung tissue and/or fluid or can promote and aggravate conditions conducive to development of fibrosis generally and (d) in a consultative capacity he may be called upon to give expert evidence in cases of disputed claims to compensation under the various silicosis and asbestosis schemes obtaining.

As a guide to the various rocks concerned with silicosis and asbestosis, a summary of the compensation schemes at present in force in this country and the particular industries affected is given to aid the petrologist who may be concerned either academically or professionally with this matter. It may be remarked, however, that the whole question of silicosis and asbestosis, their causes, effects and position under the general

¹ T. Legge, "Industrial Maladies." (Oxford University Press, London), 1934. p. 181.

Workmen's Compensation Acts is now under revision in the light of intensive researches being carried on by the competent authorities and we may confidently expect in the near future drastic revision of statutory rules and orders as at present framed.

The Sandstone Industry (Silicosis) Scheme, 1931, S.R. & O., 1931, No. 346 (superseding S.R. & O., 1929, No. 171).

The sandstone industry for the purpose of this scheme refers to "all processes in or incidental to the getting or manipulation of sandstone with a view to manufacture, sale or use, which are carried out on at or within the close or curtilage of any mine or quarry or at any premises worked in conjunction with a mine or quarry, wherever situate." Sandstone includes ganister, gritstone and quartzite rocks, but not rotten stone or natural sand. The scheme does not apply (1) to premises already covered by the Refractories Industries (Silicosis) Scheme, 1931; (2) to any premises not part of a mine or quarry where silica flour is manufactured from sandstone; (3) to any mine or quarry where sandstone is worked only occasionally and even then without the aid of explosive or mechanical power; (4) to engineers, blacksmiths etc., working in a mine or quarry but not actually engaged in the part of the premises devoted to processes covered by the Scheme; (5) to processes for the manufacture of artificial stone except breaking, crushing and grinding of sandstone and incidental handling. See, however, the Various Industries (Silicosis) Scheme, 1931 (S.R. & O., 1931, No. 342).

Exemption may be claimed from the scheme by employers who show that the sandstone got or manipulated at any mine, quarry or other premises does not contain more than 50 per cent. total silica.

The method approved by the Government Chemist for the determination of total silica for the purpose of this scheme is given below :—

1. "A representative sample of the material shall be taken by an expert sampler. The size of the sample will depend on the homogeneity and texture of the material.

2. "The sample shall be broken into pieces of such a size that they may easily be inserted into the percussion mortar to be used in the later stages of pulverization. After it has been

thoroughly mixed, the broken material must be "quartered down" to a bulk of about half a pound, and then crushed in a steel percussion mortar until the whole will pass through the topmost of a battery of six sieves whose mesh is graded from 5 I.M.M.¹ (topmost sieve) to 100 I.M.M.¹ (lowest sieve). The fractions retained by each sieve after a thorough shaking shall be separately mixed, weighed, and such aliquot portions taken from each that there is obtained a final combined sample of all grades weighing not less than 10 grams. This shall be shaken again in the battery of sieves and the coarser portions crushed in the percussion mortar until the whole passes through the 100 sieve. The final powder shall be thoroughly mixed and transferred to a closed bottle. Gross particles of iron are to be removed from the powder by means of a magnet.

3. "1 gram of the finely powdered sample is to be mixed with 4 grams of pure anhydrous sodium carbonate in a platinum crucible, the mixture being covered with a further 1 gram of the sodium carbonate. The crucible and contents shall be heated over a Teclu or Meker burner, at first gently, the heat being gradually raised to the full and so maintained for 20-30 minutes until the contents are in a state of quiescent fusion. After a final heating for 5 minutes over the blast, the crucible shall be cooled by quenching in cold water, and the fused cake removed and disintegrated by heating with water in a platinum dish. 15 millilitres of concentrated hydrochloric acid (Specific Gravity 1.15) shall then be added slowly, the dish being covered, and after effervescence has ceased, the liquid shall be evaporated to dryness over a steam bath, heating being continued until the bulk of the hydrochloric acid is removed and the deep yellow colour of the iron chloride has changed to a pale yellow. The dry mass shall be drenched with about 5 millilitres of concentrated hydrochloric acid, 100 millilitres water added, and, after solution of the soluble salts by heating, the whole shall be filtered and the silica washed first with cold water and finally with hot water until free from chlorides. The filtrate shall be evaporated again to dryness, the mass treated with hydrochloric acid and water as in the first evaporation, and the small amount of silica filtered off, and washed on

¹ I.M.M. signifies the scale of sieves adopted by the Institute of Mining and Metallurgy.

a separate filter paper. The combined filter papers and silica etc. shall be dried and ignited, finally over the blast, in a weighed platinum crucible until the weight is constant (A). A few drops of water, 5 drops of sulphuric acid (1 : 1), and 10 millilitres of pure hydrofluoric acid shall be added to the crucible and the silica volatilised by evaporation to dryness on a hot plate. The crucible and residue shall be ignited and weighed (B); the difference between (A) and (B) gives the weight of silica in the sandstone taken.

"A blank experiment must be carried out at the same time, using the same number of filter papers and similar quantities of reagents."

Refractories Industries (Silicosis) Scheme, 1931 (S.R. & O., 1931, No. 345, superseding S.R. & O., 1919, No. 12 and S.R. & O., 1925, No. 79).

This scheme covers the getting, handling, moving, breaking, crushing, grinding, or sieving of material containing not less than 80 per cent. total silica (*e.g.* ganister) and the manipulation of such material in the manufacture of bricks or other materials containing not less than 80 per cent. total silica.

Various Industries (Silicosis) Scheme, 1931 (S.R. & O., 1931, No. 342, superseding S.R. & O., 1928, No. 975 and S.R. & O., 1930, No. 1095).

The scheme covers a variety of processes not included under the Refractories Industry and Sandstone Industry Schemes, the chief of which are given below:—

- (1) Mining and quarrying in silica rock, which for the purposes of the scheme means quartz, quartzite, ganister, sandstone, gritstone and chert, but does not include sand or rotten stone.
- (2) Drilling and blasting in silica rock incidental to the quarrying or mining of other minerals.
- (3) Sawing, planing, dressing, shaping, cutting or carving silica rock or granite or any igneous rock, but excluding kerb dressing in the case of granite and igneous rocks.
- (4) Breaking, crushing, grinding, sieving, mixing, packing, handling, removing silica rock, dried quartzose sand or some other materials of high silica content. This may include workmen engaged in laying concrete or mixing tar or asphalt macadam, should dry siliceous aggregates be employed in these processes.

- (5) Certain processes involving exposure to ground flint dust in the pottery industries.
- (6) Fettling of steel castings.
- (7) Sand blasting in foundries or metal works with quartzose sand, crushed flint or silica rock.
- (8) Underground and surface operations at tin mines.

It will be noted that the deciding factor is the geological nature of the rock, not its free or total silica content. Chemical analysis is therefore unnecessary except in so far as it may be required to confirm the geological interpretation. In such cases, the total silica is determined by the method given above and free silica by the method of A. Shaw, which is as follows:—¹

"Five grms. of the sample, ground to pass 60-mesh I.M.M., are mixed with 300 ml. of dilute hydrochloric acid (2.5 per cent. by vol.), and heated to boiling in a deep porcelain dish of 1,300 ml. capacity. The dish is allowed to stand for 2 hours, or until the material has settled, and the clear liquid is syphoned off. It is advisable to have a tap or pinch-cock in the syphon tube to reduce the rate of flow towards the end of the operation; if the syphon is clamped so that the end of the short limb is adjustable in the liquid, it will be found possible to remove practically the whole of the solution without disturbing the solid material. The residue is stirred with 100 ml. of water, 100 ml. of sulphuric acid (1 : 1 by vol.) are added, and the mixture is boiled, with frequent stirring, until acid fumes are freely evolved. The temperature of the solution should not rise above 200°C., and the total time of evaporation should be approximately 45 to 60 minutes. The dish is allowed to cool for 30 minutes, and its contents are diluted with a litre of water, well stirred and allowed to settle. The clear solution is syphoned off, and the residue is treated with 100 ml. of water and 100 ml. of the sulphuric acid and evaporated once more. After dilution, and settling and syphoning off the solution, the residue is neutralised with Lunge solution (100 gms. of crystallised sodium carbonate and 10 gms. sodium hydroxide in 1 litre of solution).

"If the amount of acid liquid remaining in the dish is large (20 ml. or more), 50 per cent. sodium hydroxide solution

¹ *The Analyst*, 59, 700, 1934, p. 446.

should be used for neutralisation, to prevent excessive dilution of the Lunge solution in the following operation. Three hundred ml. of Lunge solution are then added, and the liquid is heated to boiling, with frequent stirring. After standing for two hours the solution is syphoned off, and the residue is boiled for 5 minutes with 500 ml. of concentrated hydrochloric acid, diluted to one litre, and allowed to settle. The acid solution is syphoned off, the residue is neutralised with Lunge solution or 50 per cent. sodium hydroxide solution, 150 ml. of Lunge solution are added, and the liquid is heated to boiling. After standing for two hours, the Lunge solution is syphoned off, and the residue is boiled for five minutes with 200 ml. of concentrated hydrochloric acid. Two hundred ml. of water are then added, and the liquid is filtered through a Whatman No. 40 filter. The residue is transferred to the filter, washed twice with hydrochloric acid (1 : 3 by vol.) and then with water, until the washings are free from chlorides and, finally, ignited to constant weight in a tared platinum crucible. To the ignited residue are added 5 ml. of water, 5 to 10 drops of concentrated sulphuric acid and 15 ml. of hydrofluoric acid, and the resultant liquid is evaporated on a hot plate until sulphuric acid fumes are evolved. The evaporation is repeated with two further quantities of hydrofluoric acid, heating being continued during the final evaporation until sulphuric acid fumes are *freely* evolved, to ensure complete removal of fluorine, which would interfere with the determination of alumina in the residue. The contents of the crucible are extracted with water, and the solution is filtered. The alumina in the extract is then determined in the usual way by precipitation with ammonia, methyl red being used as indicator to avoid excess. The weight of alumina, multiplied by 5.41, gives the equivalent weight of potash feldspar, and this, subtracted from the weight of the ignited residue previously determined, gives the amount of quartz or free silica in the sample.

"The above method differs from that of W. A. Selvig¹ in the use of a syphon in preference to decantation, the grinding of the sample to pass 60-mesh I.M.M. instead of 200 and the removal of silica from the residue by evaporation with hydrofluoric acid instead of by fusion with sodium carbonate and

¹ *Carnegie Inst. Tech. Min. and Met. Invest. Bull.* 21, 1925.

separation of the silica by evaporation to dryness with hydrochloric acid."

Metal Grinding Industries (Silicosis) Scheme, 1931 (S.R. & O., 1931, No. 343 (superseding S.R. & O., 1927, No. 380 and S.R. & O., 1930, No. 118).

The Scheme applies to processes involving the grinding of metals on grind stones composed of natural or artificial sandstone.

The Asbestos Industry (Asbestosis) Scheme, 1931 (S.R. & O., 1931, No. 344).

The inhalation of asbestos dust produces a type of fibrosis in the lungs resembling silicosis in its general features although differing in certain clinical aspects, *e.g.* the nodular structure of the fibrosis is very much less marked and tuberculosis supervenes less frequently. The disease attacks workers engaged in disintegrating raw asbestos or in manufacturing cloth and other textiles from the fibre, as well as those employed in grinding, sawing etc. manufactured products containing substantial amounts of asbestos. Means of protection similar to those adopted for silicosis have proved successful. Provision is made in the scheme for the protection of workers in the following processes:—

- (1) Grinding, crushing, sieving etc. of asbestos or asbestos mixtures.
- (2) Manufacture of the fibre into textiles, mattresses etc.
- (3) Sawing, turning, and grinding of manufactured articles containing asbestos (*e.g.* asbestos board) except those in which bitumen is used as the bonding agent.

Theories Regarding the Cause of Silicosis.

The Government regulations infer that "free silica" (quartz) is the cause of silicosis, but some doubt has been cast on this assumption by the work of W. R. Jones,¹ who concludes that the main cause is not free silica, but the fibrous silicates, such as sericite ("secondary white mica"). In the course of an inspection of the collieries in the anthracite district of the South Wales coal field, he failed to find quartz, quartzite, sandstone, gritstone and chert in some of the working places where silicosis had been contracted and it appeared probable

¹ *Journ. Chem. Met. and Min. Soc., South Africa*, 34, 1933, p. 99.

that rocks other than the above were capable of giving rise to a silicosis-producing dust. An examination of the mineral constituents in a number of silicotic lungs revealed the fibrous hydrated silicate of aluminium and potassium (sericite) as the chief constituent present and subsequently this mineral was also found in all rock types giving rise to silicosis. The sericite detected in the silicotic lungs was in the form of minute fibres $0.5\text{--}2\mu$ in length and much smaller in size than the grains of quartz which were also present. The number of fibres present is therefore greatly in excess of the number of grains of quartz or of the other constituents. Sericite is frequently found in quartz-bearing rocks, but not always. W. R. Jones points out that the gold-bearing quartz of Kolar, India, contains over 90 per cent. free silica, yet silicosis is not known in the mines, whereas in South Africa where the free silica content of the gold-bearing quartz (Banket) is 80-90 per cent., silicosis is very prevalent. On the other hand, sericite is present in abundance in the South African rock, but not in the Indian. Similarly, silicosis is common in the South Wales coal field, but not in any other in the British Isles. This difference could not be ascribed to the nature of the quartz grains (since the South Wales sandstone grains are very similar to the Scottish) but to the fact that sericite is found in the sandstone overlying the South Wales coal measures, but not in other districts. Again, in a gold mine in Rhodesia, quartz has been drilled for twenty years without the occurrence of silicosis, whereas, on the other hand, workers engaged in crushing cryolite containing only 3 per cent. of free silica have developed symptoms. Cases, too, are known where sillimanite and other fibrous minerals have caused silicosis. W. R. Jones, therefore, considers that pure quartz cannot be the principal constituent of dusts giving rise to silicosis and he regards the fibrous silicates as far more dangerous, although quartz may act in some secondary manner.

The theory is regarded by some authorities as inconclusive and it has been suggested that the difference in the prevalence of silicosis in the mines quoted may be due to the varying effectiveness of the precautionary measures rather than the presence or absence of sericite. Further, the presence of sericite in the lung is not proof that it is the cause of silicosis. It is

possible for free silica to be the cause, but to be preferentially dissolved by the body fluids.

F. S. Fowweather¹ compared the amount of silica in lungs with the degree of fibrosis, but was unable to make any direct correlation. He arrived at the conclusion that the amount of silica present is not the only factor influencing fibrosis. His experiments indicate that some forms of silica are more dangerous than others and that, as is the case with other diseases, some individuals are more prone to infection than others. Pure silicosis unaccompanied by tuberculosis, bronchitis, pneumonia etc. is found to be comparatively rare. He concludes that the soluble alkali silicates are the most dangerous forms of silica as far as giving rise to silicosis is concerned.

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¹ *Journ. Soc. Chem. Ind.*, 53, 20, 1934, p. 448; 53, 33, 1934, p. 713.

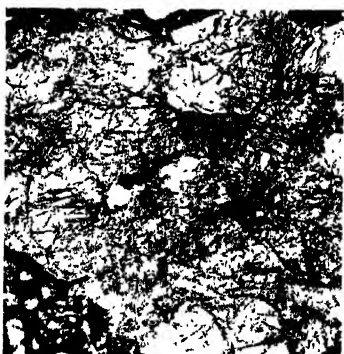
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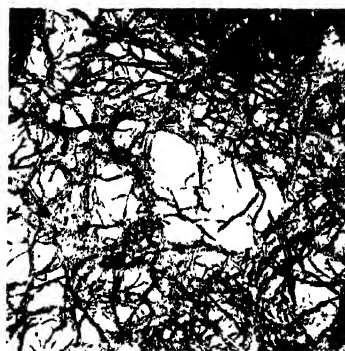
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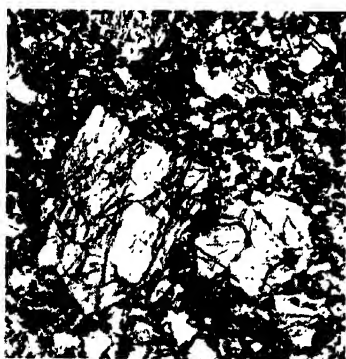
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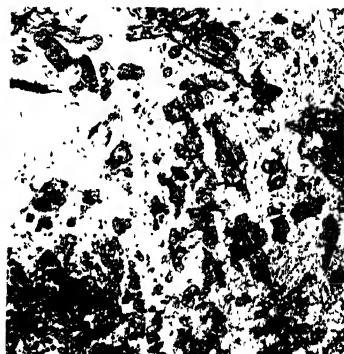
C



D



E



F

A, B. RAW MATERIALS FOR REFRACTORIES.

A. Magnesite, Salzburg, Austria [x 22.]

B. Sillimanite, India. [x 18.]

C-F. REFRACTORY PRODUCTS.

C. Siliceous Brick. [x 43.]

D. Silica Brick. [x 43.]

E. Silica Brick. [x 19.]

F. Cristobalite and Tridymite. [x 39.]

To face page 589.

PLATE 52.

Refractories.—The selection of suitable raw materials for manufacture of all kinds of refractory products has for long been governed by extensive laboratory tests now almost universally involving *inter alia* microscopical examination of the natural rocks, equally the fired products, as well as other standard petrographic methods for determining mineral composition and physical characteristics. Of these raw materials, the chief are :—

Alumina.	Fluorite.
Ball clay.	Ganister.*
Bauxite.	Graphite.
Chalk.	Limestone.
China clay.	Magnesite.
Chromite.	Quartzite.
Diatomite.	Sand.
Dolomite.	Silica rock.†
Fire clay.	Sillimanite.

* Including Bastard Ganister.

† Including Vein Quartz.

Each of these substances is petrologically studied in accordance with conventional procedure, either by thin section or slides of incoherent particles, whichever is the more applicable; from this, pertinent evidence of great practical value is secured. Such investigations if skilfully performed and properly interpreted with sound knowledge of the varying processes in which one or more of those components are involved, never fail to throw considerable light on their ultimate behaviour on grinding, crushing, mixing and, most important of all, firing. In fact, in so far as the petrographic investigation of any final product is concerned, it is impossible to understand this completely from a petrological standpoint unless some knowledge of the raw materials initially employed has been gained.

With one or more of the above materials as a basis, the following are the varying types of products manufactured in this industry today :—

Acid-resisting bricks.	Glass-furnace bricks.
Aluminous bricks.	Insulating bricks.
Bauxite bricks.	Insulating cements.
Chrome bricks.	Magnesite bricks.
Chrome-magnesite bricks.	Magnesite cements.
Chrome cements.	Silica bricks.
Coke-oven bricks.	Silica cements.
Dolomite bricks.	Siliceous bricks.
Firebricks.	Sillimanite bricks.

Microscopical examination of products such as these calls for a great deal of experience and specialised knowledge of materials and processes. In so far as ordinary petrological examination is concerned, the technique of impregnating sections of refractories with synthetic resin (p. 42) has helped enormously in their preparation and interpretation. Incidentally, it is important to note that thin sections should be much larger for this sort of work than is normally attained with ordinary sedimentary rocks.¹

Each type must necessarily be dealt with on its own merits, depending on the original constitution of the mix, the nature of the firing cycle and the degree of conversion aimed at and achieved, or otherwise. For example, with silica bricks, these are examined for degree of inversion sustained by original quartz particles, for the nature, shape, proportion and size of voids, as revealed by the coloured resin, particle size and internal structure. Relative proportions of unaltered quartz, tridymite, cristobalite and associated silicates must be assessed and correlated with chemical analyses. In this work, the polarising microscope is used, not only with thin sections, but also in the examination of fragments from crushed bricks which are generally identified by refractive index (immersion) methods. V. L. Bosazza has successfully employed "Polaroid" polarisers in conjunction with wide-field binoculars for this work.²

Identification of artificial minerals is a specialised field of study and it must be admitted that in a number of cases of refractory products, it is impossible to determine the whole mass completely or to give a name to some of its components whose complexity of composition defies expression in terms of known minerals. Considerable aid in such research will, however, be obtained from A. N. Winchell's well-known textbook.³ In pursuing work of this character it is essential to have a large reference collection of thin sections and other relevant mounts,

¹ V. L. Bosazza, "A Note on Petrographic Methods Applied to the Study of Silica Bricks." *Trans. Ceram. Soc.*, 37, 1938, p. 1.

² *Op. cit.*, p. 2.

B. M. Shaub, "On the Use of 'Polaroid' for the Photography of large thin sections in Crossed Polarised Light." *Amer. Mineral.*, 21, 1936, p. 384.

³ "The Microscopic Characteristics of Artificial Inorganic Solid Substances or Artificial Minerals." (Chapman and Hall, London), 1931.

not only of raw materials commonly used in this country, Germany and the United States etc., but particularly of the varying types of refractory products produced therefrom. It will also be found useful to refer to slides of pre-determined artificial minerals, such as cristobalite, tridymite, mullite etc., and equally to isolated fragments of these minerals and other silicates which are continually being revealed in different types of refractory bodies, the refractive indices of which have previously been determined.

In another direction, the science is concerned with selection of refractory sands for furnace and foundry purposes, a field explored in great detail by P. G. H. Boswell during the war.¹ Such sands are used primarily for lining and repairing Siemens' open-hearth furnaces, for acid-production of steel, for beds of re-heating furnaces and soaking pits, for making moulds in which different metals are cast, for preparation of silica bricks and, mixed with other materials, for making crucibles, "ganister" for lining cupolas etc. and other refractory bodies.²

In the case of sands employed for fettling furnaces, certain moulding mixtures, soaking pits, silica and siliceous bricks and the like, mineralogical purity is essential, the fundamental constituent being quartz. Chemical analyses of suitable sands for these purposes usually show between 96 and 99 per cent. silica with as low a percentage of alumina and alkalis as possible. Mechanical analyses of these sands are equally important and indicative, but grade composition of the quartz particles necessarily varies with the particular use to which the raw material is put. Similarly, moulding sands possessing a natural bond and used for iron, steel and non-ferrous castings have been critically studied from petrographical and chemical standpoints and the desiderata of selected high quality sands thus established.³ A high percentage of silica, adequate clay or ferruginous bond or both and appropriate grading, collectively determine maximum refractoriness, cohesiveness and permeability to gases at high temperatures.

1 "Memoir on British Resources of Refractory Sands for Furnace and Foundry Purposes." (Taylor and Francis, London), 1918.

2 P. G. H. Boswell, *op. cit.*, p. 35.

3 P. G. H. Boswell, *op. cit.*, p. 67.

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The following periodicals should be consulted :—

- British Refractories Research Association (Publications).
 Journal of the American Ceramic Society.
 Journal of the Society of Glass Technologists.
 Proceedings of the American Society for Testing Materials (also Specifications and Methods of Test).
 Refractories Journal.
 The Foundry.
 The Foundry Trade Journal.
 Transactions of the American Foundrymen's Association.
 Transactions of the Ceramic Society (including Refractory Materials).

Water Supplies.—Of all natural commodities available to mankind, water is the one most often taken for granted, a high standard of quality and adequate quantity being tacitly assumed; it takes either a fever epidemic or a severe drought to focus suddenly public attention on what is unquestionably the most vital factor in everyday life. Purity of supply is a matter for the chemist and bacteriologist. Quantity concerns both geologist and engineer.

It is somewhat surprising to note how conventional geology of water supplies has become in this country, often largely a matter of reconnaissance, field-survey, advice as to suitable sites for wells, borings or reservoirs, the tabulation of existing bore-hole data, identification of bore-hole samples; to these must be added assessment of catchment area, rainfall, effective underground percolation and estimates of supplies at

any one point. All this is part of the hydrogeologist's stock-in-trade.

The occasions, however, when porous sub-surface reservoir rocks, such as sands, are studied in the same thorough manner as was done by F. H. King¹ in his classical contribution to the science on "Principles and Conditions of the Movements of Ground Water" are relatively rare in this country; yet the data to be obtained from similar, even though far less detailed, research are invaluable in accurate assessment of supplies, direction of flow of underground water, significance of chemical composition (dissolved salts) and in solving problems of base-exchange. Time and again cases arise where cores from deep borings are vested with amazing palæontological glamour with little, if any, consideration being given to the actual rock-types involved, which act underground as controlling factors in determining the real characteristics of the water thus made available.

Sedimentary petrology properly adapted can more than hold its own in this field; especially should this be the case in future when increasing demands will inevitably be made for pure, softer and deeper-lying underground water supplies. It does not matter whether the rocks are sandstones, limestones, chalk, gravel or any other favourable type; as sub-surface, natural water-reservoir rocks, they should invariably be studied at the outset of any new undertaking and petrographic methods employed to the full in determining their unseen characteristics at any particular site.

Such important British water-producing sands as the Bunter, Upper Lias, Lower Greensand and Eocene are excellent examples of deposits which have, from a purely hydrological standpoint, received close attention in everything but fundamental properties. Relevant data of this description have admittedly from time to time been accumulated by various investigators, not necessarily geologists. Only occasionally, however, is the work published; more often it lies buried in confidential reports in the archives of public water undertakings; a plea may be made here for its disinterment and appearance in technical literature. To apply the principles and practice of sedimentary petrology to problems concerning

¹ *U.S. Geol. Surv., 19th Ann. Rep., 1897-98, p. 67.*

water-bearing strata is not academic, but an obvious modern method of elucidating hydrostratigraphical problems. It is not merely a case of descriptive mineralogy. In fact, in a majority of instances, "heavy mineral" work is of little import. On the other hand, there are many weapons in this armoury which might be used far more vigorously and with certainty of important economic results than is at present general. To illustrate such applications, a few actual cases may be quoted from the author's own experience.

1. Two deep borings were put down on a chosen site, one situated within 50 feet of the other. The first failed owing to excessive running sand and to subsequent inability to counter it, although a supply could undoubtedly have been developed there. The second showed at comparable depth no tendency whatever to running sand and, moreover, proved a failure from the standpoint of water yield. Samples had been taken during the run of both borings and these had been carefully preserved, but casual examination had not provided any clue to the reason for such marked diversity of behaviour in the two holes.

Before proceeding further with the scheme, a critical microscopical study was undertaken of representative samples of the sands involved. In the case of No. 1 boring, the samples showed a relatively clean quartz sand of mixed grade and sub-angular particles; the absence of authigenic matter was marked and from every standpoint the sand appeared to be an ideal type for underground water percolation. In the case of the suite of samples chosen from No. 2 bore-hole, these appeared externally to be heavily limonitised quartz sands until the interior of certain of the samples was extracted, when the grains had an obvious green coating. Critical examination revealed this mineral to be ferrous carbonate, subsequently confirmed chemically and this ferrous carbonate when exposed to the atmosphere rapidly oxidised and changed colour. An examination of a large number of samples showed, in fact, that this ferrous carbonate was a copious constituent of the sands throughout the particular section from which a good supply of water had been anticipated and it was clear that its presence in such quantities in the deposit was sufficient to reduce permeability to a minimum. Deepening the boring to the base of this deposit gave no relief and the site had to be

abandoned. It was therefore decided to return to the old site and, by making adequate provision to trap the mobile sand, a new bore-hole was put down from which a satisfactory supply was obtained.

2. A bore-hole in the chalk, for some time yielding a regular supply of water of hardness 25 parts per 100,000, suddenly failed: all efforts to bring it back again proved fruitless. The boring was deepened in the hope of striking further fissures in the chalk, but this was unsuccessful, even when carried right to the base. It was, therefore, decided to bore further in the underlying Greensand. Progress of boring was controlled in this Greensand by petrological examination of samples recovered every 3 feet with two objectives:—

- (a) to reach a horizon known in the district to be productive,
- (b) to penetrate a pre-determined thickness of sandstone below this horizon to give optimum inflow into the pump.

Some 50 feet of strata were thus involved in critical examination. The samples recovered had the appearance of normal Greensand and the heavy mineral suites, where examined, were characteristic. The desired section in the Greensand was penetrated accordingly and a satisfactory supply obtained. Chemical analysis of the water from this horizon, however, revealed a surprising change in its hardness, which was now returned at 3 parts per 100,000. It was decided to investigate the cause of such an unusual supply. Renewed petrological examination of the samples showed that the amount of glauconite present in this Greensand was unusually high and there is no doubt that the excess of this mineral had brought about a natural base-exchange whereby the calcium and magnesium salts in the water were replaced by sodium. Cases of this kind are of course well known in connection with Greensand and also Eocene waters, but this particular instance is exceptional in the extremely high concentration of glauconite at this place.

3. The ultimate source of water-borne sediment is often of importance in problems concerning its removal from public supply. In some instances this sediment has a decided nuisance value at the waterworks themselves, *e.g.* in wells, headings and borings, if not further afield in mains and reservoirs. Headings to wells frequently get coated with iron

oxide, "foreign" silt etc., especially where they are fed by a system of borings to deeper lying horizons than those in which the headings are actually cut. In other cases, *positive knowledge* that water-borne sediment has been derived from a definite stratigraphical horizon can determine its elimination by suitable lining-out of the undesirable section of an existing or projected bore-hole.

Most cases of copious iron oxide deposition are due to bacteriological causes. Generally speaking, it is rare to find this in deep bore-hole supplies, providing there is no contamination from surface water; but where the gathering ground is not well protected and particularly where the rocks through which the water flows are heavily charged with iron, then given favourable conditions, iron bacteria will flourish and, unless prevented, may cause considerable trouble.¹ It is in cases such as these that a knowledge of the mineral composition of the rocks involved is of paramount importance and sedimentary petrography has been used to great advantage, in conjunction with chemical and bacteriological analyses, to determine the source of such undesirable constituents in the water, whether deposited or in the form of suspended matter.

It is clear that where lithological changes are encountered in any bore-hole section, for instance where limestones and clays alternate, not only the quality of the water itself, but the nature of the sediment, if present, will be dependent to a large extent on whether the water is flowing through unlined or lined holes. The examination of such a sediment either directly or by means of its heavy mineral suite, compared with similar material of known origin in the area, has in more than one instance afforded a complete solution to problems of sediment contamination of water supplies which has enabled schemes to be worked out for its prevention, either at the existing site, or more particularly where new works involving similar rocks are envisaged. Cases such as the above have been worked out in the author's laboratories and it is seldom that appeal to the petrology of the sediment or solid rocks involved, coupled with intelligent interpretation of available chemical analyses, has not provided positive clues to local conditions on which satisfactory remedial measures have, in consequence, been defined.

4. In certain problems of filtration, selection of suitable

¹ D. Ellis, "Iron Bacteria." (Methuen, London), 1919.

sands for this purpose is an important matter. Apart from choice of sand possessing desirable physical characteristics, its employment must be governed primarily by biological factors. For instance, it is often necessary firstly to determine the algal and/or diatomaceous and/or bacterial organisms present in the water concerned before selecting the sand and this may be taken as generally desirable procedure. Construction and particularly constitution of sand filters depend inevitably on the degree of purification aimed at. Sand filtration may be "slow," *i.e.* natural percolation or "rapid," in which case a mechanical contrivance is installed periodically to clean the sand.

The British Waterworks Association has laid down a brief specification for sand (in a 2 ft. layer) which should conform to the following grading:—

Circular mesh $3/16$ inch	...	...	All passes.
Square mesh $1/25$ inch	...	...	70 per cent. passes.
Square mesh $1/70$ inch	..	..	10 per cent. passes.

The equivalent B.S. specification is as follows:—

$3/16$ inch sieve	..	...	...	All passes.
16 inch sieve	...	...	...	70 per cent. passes.
44 inch sieve	...	...	..	10 per cent. passes.

An example of the choice of a sand suitable for the above and recently worked out gave a grading as follows:—

$3/16$ — 16	...	...	...	30 per cent.
16 — 44	...	...	...	60 per cent.
— 44	...	...	...	10 per cent.

Sand conforming to this specification was clean, free from silt and clay, sub-angular in grain and had a loose (initial) porosity of 42 per cent. This example illustrates quite a simple problem of sand selection for a specific filtration purpose and it also implies the use of the microscope in determining optimum physical characteristics, quite apart from grading factors. Porosity in these cases is determined in accordance with the method given in Chapter VIII, p. 203.

5. It is relatively seldom that *geochemical* analyses of water, implying critical geological interpretations of the inorganic constituents revealed by chemical analysis, are undertaken in this country; but they form a regular feature of the research work on water supplies carried out in the author's

Geochemical Laboratories Reference No.	I. 1334B	II. 1334C	III. 1334D	IV. 1334F
Albuminoid nitrogen	0.0126	0.0104	0.0091	0.0088
Ammoniacal nitrogen	0.0023	0.0011	0.0013	0.0023
Nitrate nitrogen	0.01	1.80	2.81	0.39
Nitrite nitrogen	Nil.	Nil.	Nil.	Nil.
Oxygen absorbed				
(3 hrs. at 37°C.)	0.220	0.070	0.070	0.090
Iron (Fe)	<0.002	<0.002	<0.002	<0.002
Copper (Cu)	<0.001	<0.001	<0.001	<0.001
Lead (Pb)	<0.01	<0.01	<0.01	<0.01
SALINE CONSTITUENTS.				
SiO ₂	0.5	0.3	0.7	0.6
Fe ₂ O ₃ , Al ₂ O ₃	0.0	0.0	0.0	0.0
CaO	11.5	15.4	22.2	15.9
MgO	0.1	0.1	4.2	0.2
CO ₂	9.0	8.1	16.0	10.3
SO ₃	1.8	5.4	6.0	5.2
N ₂ C ₅	—	7.3	10.8	1.5
Chlorine in chlorides	0.8	2.7	3.7	2.2
Na ₂ O	1.6	5.1	6.3	4.7
K ₂ O	0.3	0.3	0.3	0.3
Total solids (dried at 180°C.)	26.9	49.7	77.4	41.3
HARDNESS (Soap Solution).				
Temporary	16.0	18.0	39.8	21.0
Permanent	3.9	12.0	23.0	8.1
Total	19.9	30.0	62.8	30.0
THEORETICAL COMBINATIONS.				
CaCO ₃	20.6	18.4	36.3	23.4
CaSO ₄	—	8.2	4.6	6.8
CaCl ₂	—	2.6	—	—
MgCO ₃	—	—	—	—
MgSO ₄	0.3	—	5.0	0.6
MgCl ₂	—	0.3	5.0	—
Mg(NO ₃) ₂	—	—	1.4	—
Na ₂ CO ₃	—	—	—	—
Na ₂ SO ₄	2.8	—	—	1.4
NaCl	0.8	1.5	—	3.6
NaNO ₃	—	11.5	15.4	2.4
KCl	0.5	—	—	—
SiO ₂ & silicates	0.5	0.6	1.4	1.2
	25.5	43.1	69.1	39.4

IN PARTS PER 100,000.

V. 1122	VI. 1120	VII. 1241C	VIII. 1388B	IX. 1236E	X. 1236S
0.0097 0.0688 0.09 Nil.	0.0079 0.0258 0.22 Nil.	0.0030 0.0218 0.01 Nil.	0.0117 0.0018 0.18 Nil.	0.0030 0.0056 0.37 Nil.	0.0062 0.0006 0.02 Nil.
0.050 — —	0.053 — —	0.008 — —	0.006 <0.002 <0.001 <0.1	0.012 — —	0.063 — —
0.6 0.0 15.9 6.8 12.8 6.0 — 6.9 — —	7.2 0.4 38.9 25.2 16.6 66.6 — 3.6 — —	1.0 0.0 8.6 0.4 11.0 4.8 — 6.3 11.9 0.2	0.7 0.0 12.4 0.8 9.0 1.4 0.7 0.9 1.4 0.1	0.9 0.0 15.1 0.1 12.5 4.4 — 1.5 8.0 0.1	1.6 0.0 12.5 0.2 13.8 2.8 — 6.4 12.4 0.2
62.1	175.7	42.4	28.5	46.0	57.2
29.1* 16.1* 45.2*	39.1 101.5 140.6	16.7 5.9 21.7	21.6 4.1 25.7	29.1 9.4 38.5	23.2 8.1 31.3
28.4 — — 0.6 9.0 8.2 — — — 1.3 0.6 — 0.6	37.3 43.2 — — 61.8 4.8 — — — — 0.3 — 7.2	15.4 — — 0.8 — — — 9.2 8.5 5.3 — 0.4 1.0	20.5 2.3 — — — 1.2 0.7 — — — 0.3 — 1.4	27.0 — — 0.2 — — — 1.2 7.8 2.5 — — 2.7	22.3 — — 0.4 — — — 9.8 5.0 9.1 — 0.3 1.6
48.7	144.6	41.2	26.4	41.4	48.5

* Calculated from saline constituents.

laboratories. Differentiation and/or correlation of sub-surface waters by appeal to chemical analyses is a well-known and standardised technique in most oil-field laboratories, where water sands (implying for the most part connate water) have to be identified, sealed off or otherwise taken into account. Such differentiation often has direct bearing on problems of sub-surface stratigraphical correlation. Similarly, in normal hydrogeological studies comparison of chemical analyses of waters from different known horizons in a local geological column more often than not provides the reason for particular or peculiar characteristics of the waters involved and may sometimes have definite bearing on stratigraphical problems, sub-surface structural features and lithological variations.

Other things being equal, the quality of a water from a chemical standpoint is determined primarily by its lithological environment. Changes in constitution undergone by water from the moment of its incidence on the land-surface until ultimately it reaches the site from which it is being drawn, are necessarily influenced directly by the nature of the rocks through which it flows, quite apart from any subsequent organic influence which may intervene to change fundamental characteristics; this is even more pronounced where flow is retarded, pumping decreased or suspended or in cases of underground stagnation when salinity may reach abnormal proportions; the latter condition has been well exemplified in the case of Lower Oolite water blanketed under Oxford Clay in Wiltshire, some miles in from the contact-outcrop.

An informative series of analyses in illustration of the above remarks has been selected from a number made in the author's laboratories on water from the Bristol district; these are now published by permission of the authorities concerned. In comparing them note should be taken of the rock-types involved and, incidentally, of the relevant stratigraphical horizons.

- I. Sandstones and Grits (Silurian).
- II. Sandstone (Old Red Sandstone).
- III. Limestone (Carboniferous).
- IV. Grits (Millstone Grit).
- V. Sandstone (Pennant Grit, Coal Measures).
- VI. Gypsiferous Marl (Keuper Marl).
- VII. Sand (Cotteswold Sands, Upper Lias).
- VIII. Oolitic Limestone (Inferior Oolite).
- IX. Limestone (Great Oolite).
- X. Clay (Oxford Clay).

In tracing the relationship between characteristics of a given water and inorganic features of its particular reservoir rock, detailed mineralogical examination of outcrop type at the gathering ground, of sub-surface samples of the corresponding deposit at site, combined with full chemical analyses of samples of the water concerned (as above) must be made. Admittedly in certain cases results are inconclusive as, for example, where sources and/or direction of flow are doubtful or multiplied or where contamination from surface water or other underground water at or near the site is manifest or probable. But it is the author's experience that in a majority of cases comprehensive chemical and petrological work of the kind herein indicated, made to supplement normal hydrogeological investigation, has everything to commend it in explaining the nature of a supply, in suggesting possibilities of new sources of supply and, particularly in the case of new works, in controlling petrologically (as well as palæontologically where relevant) well-sinking or boring progress so that the maximum amount of information may be given to the engineer in charge.

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APPENDICES.

In the second edition of this work there were included in Appendix I a series of determination tables forming a system for rapid diagnosis of detrital minerals in terms of certain physical and optical constants.

In the present edition, the list of materials has been considerably extended and inclusion of the added species in similar tables would make the latter somewhat unwieldy to work, thus defeating their original object.

The author has found by experience that, following precise determinations of such properties as specific gravity, hardness, refractive index, birefringence etc., of unknown mineral grains, diagnosis is greatly facilitated by collateral reference to relevant and separate tables listing these essential properties in order of increasing numerical values. While no originality whatever is claimed for this procedure, it is believed that reproduction of the lists in actual use in the author's laboratories will afford a comparable degree of assistance to the student as has been proved therein by their repeated use.

Such lists have an added advantage that they are applicable to rock minerals irrespective of origin and whether occurring as isolated grains or as components of thin sections. The student is, therefore, strongly recommended to study each list carefully and to make regular use of each in his practical work. By this means not only will his abilities for diagnosis be greatly and rapidly strengthened, but with constant use of these tables inherent properties of important rock-forming minerals will be gradually impressed on his mind and, incidentally, subconsciously memorised.

APPENDIX I.

Minerals arranged according to their systems of crystallisation.

ISOMETRIC (CUBIC) SYSTEM.

Allophane?	Galena	Picotite
Almandine	Garnet	Pyrite
Analcite	Grossularite	Pyrope
Andradite	Halloysite?	Spessartite
Ceylonite	Hercynite	Sphalerite
Chromite	Magnetite	Spinel
Diamond	Melanite	Uvarovite
Fluorite	Periclase	

TETRAGONAL SYSTEM.

Anatase	Vesuvianite	Xenotime
Cassiterite	Viluite	Zircon
Rutile		

TRIGONAL (RHOMBOHEDRAL) SYSTEM.

Ankerite	Graphite	Ruby
Benitoite	Hematite	Sapphire
Calcite	Ilmenite	Siderite
Corundum	Magnesite	Tourmaline
Dolomite	Quartz	

HEXAGONAL SYSTEM.

Apatite	Pyrrhotite
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ORTHORHOMBIC SYSTEM.

Andalusite	Diaspore	Olivine
Anhydrite	Dumortierite	Pyrophyllite
Aragonite	Enstatite	Sillimanite
Barite	Fayalite	Staurolite
Beidellite	Goethite	Steatite
Bronzite	Humite	Strontianite
Brookite	Hypersthene	Sulphur
Celestite	Iddingsite	Thulite
Chiasolite	Lawsonite	Topaz
Chrysotile	Marcasite	Zoisite
Cordierite	Montmorillonite	

MONOCLINIC SYSTEM.

Actinolite	Diopside	Nontronite
Ægirine	Epidote	Omphacite
Allanite	Fuchsite	Orthoclase
Antigorite	Gastaldite	Ottrelite
Arfvedsonite	Gibbsite	Penninite
Augite	Glaucosite	Phlogopite
Barkevicite	Glaucophane	Piedmontite
Basaltine	Gypsum	Riebeckite
Bastite	Hiddenite	Sanidine
Biotite	Hornblende	Selenite
Chlorite	Kaolinite	Serpentine
Chloritoid	Kunzite	Spodumene
Clinocllore	Lepidolite	Steatite
Clinozoisite	Lepidomelane	Titanite
Crossite	Monazite	Tremolite
Delessite	Muscovite	Wolframite
Diallage	Nephrite	Wollastonite
Dickite		

TRICLINIC (ANORTHIC) SYSTEM.

Albite
Andesine
Anorthite
Anorthoclase

Axinite
Bytownite
Enigmatite
Kyanite

Labradorite
Microcline
Oligoclase

APPENDIX II.

AMORPHOUS MINERALS.

Agate
Allophane?
Chalcedony
Chert
Collophane

Flint
Goethite
Halloysite
Jasper
Leucoxene

Limonite
Opal
Psilomelane
Pyrolusite

APPENDIX III.

Minerals arranged in order of hardness (Mohs' scale).

NOTE. Index minerals in *italics*.

10.0	<i>Diamond</i>	6.0	Anatase	5.0	Analcite
9.0	<i>Corundum</i>	"	Andesine	"	Antigorite
8.0	Ceylonite	"	Anorthite	"	<i>Apatite</i>
"	Lawsonite	"	Anorthoclase	"	Augite
"	Picotite	"	Arfvedsonite	"	Diopside
"	Spinel	"	Augite	"	Enstatite
"	<i>Topaz</i>	"	Barkevicite	"	Goethite
7.5	Andalusite	"	Basaltine	"	Hematite
"	Cordierite	"	Benitoite	"	Hornblende
"	Hercynite	"	Brookite	"	Hypersthene
"	Sillimanite	"	Bytownite	"	Ilmenite
"	Staurolite	"	Cassiterite	"	Kyanite
"	Tourmaline	"	Chalcedony	"	Monazite
"	Uvarovite	"	Crossite	"	Periclase
"	Zircon	"	Diopside	"	Psilomelane
7.0	Almandite	"	Enstatite	"	Titanite
"	Andradite	"	Epidote	"	Tremolite
"	Axinite	"	Glaucophanes	"	Wolframite
"	Cassiterite	"	Grossularite	"	Wollastonite
"	Cordierite	"	Hornblende	"	Xenotime
"	Diaspore	"	Humite	4.5	Antigorite
"	Dumortierite	"	Hypersthene	"	Apatite
"	Epidote	"	Ilmenite	"	Kyanite
"	Kyanite	"	Kyanite	"	Pyrrhotite
"	Melanite	"	Labradorite	"	Xenotime
"	Olivine	"	Magnetite	4.0	Ankerite
"	Ottrelite	"	Marcasite	"	Antigorite
"	Pyrope	"	Microcline	"	Aragonite
"	<i>Quartz</i>	"	Oligoclase	"	Chrysotile
"	Sillimanite	"	Opal	"	Dolomite
"	Spessartite	"	<i>Orthoclase</i>	"	<i>Fluorite</i>
"	Spodumene	"	Psilomelane	"	Kyanite
"	Staurolite	"	Pyrite	"	Lepidolite
"	Tourmaline	"	Rutile	"	Limonite
6.5	Ægirine	"	Sillimanite	"	Magnesite
"	Axinite	"	Tremolite	"	Phlogopite
"	Cassiterite	"	Zoisite	"	Pyrrhotite
"	Chloritoid	5.5	Analcite	"	Riebeckite
"	Clinozoisite	"	Anatase	"	Siderite
"	Diaspore	"	Augite	"	Sphalerite
"	Epidote	"	Brookite	"	Strontianite
"	Fayalite	"	Chromite	"	Xenotime
"	Kyanite	"	Diopside	3.5	Anhydrite
"	Magnetite	"	Enigmatite	"	Ankerite
"	Marcasite	"	Enstatite	"	Aragonite
"	Olivine	"	Goethite	"	Celestite
"	Piedmontite	"	Hornblende	"	Collophane
"	Pyrite	"	Hypersthene	"	Dolomite
"	Rutile	"	Ilmenite	"	Lepidolite
"	Sillimanite	"	Kyanite	"	Magnesite
"	Spodumene	"	Magnetite	"	Phlogopite
"	Vesuvianite	"	Psilomelane	"	Pyrrhotite
"	Zoisite	"	Titanite	"	Siderite
6.0	Ægirine	"	Tremolite	"	Sphalerite
"	Albite	"	Wolframite	3.0	Allophane
"	Allanite	5.0	Actinolite	"	Anhydrite

3.0	Ankerite	2.5	Fuchsite	2.0	Kaolinite
"	Barite	"	Galena	"	Pyrolusite
"	Biotite	"	Kaolinite	"	Sulphur
"	<i>Calcite</i>	"	Lepidolite	1.5	Beidellite
"	Celestite	"	Muscovite	"	Graphite
"	Clinochlore	"	Penninite	"	Gypsum
"	Gibbsite	"	Pyrolusite	"	Pyrophyllite
"	Iddingsite	2.0	Clinochlore	1.0	Graphite
"	Lepidolite	"	Delessite	"	Montmorillonite
"	Lepidomelane	"	Dickite	"	Nontronite
"	Muscovite	"	Glaucosite	"	Pyrophyllite
"	Phlogopite	"	Graphite	"	<i>Steatite</i>
2.5	Biotite	"	<i>Gypsum</i>		
"	Clinochlore	"	Halloysite		

APPENDIX IV.

Minerals arranged in order of specific gravity.

1.86 ...	Allophane	2.60 - 2.62	Beidellite	2.72 - 2.74	Pyrophyllite
2.06 ...	Sulphur		Chalcedony		Steatite
2.10 ...	Opal		Collophane	2.74 - 2.76	Collophane
2.20 - 2.24	Analcite		Cordierite		Glaucouite
	Glaucouite		Dickite		Iddingsite
2.24 - 2.26	Analcite		Glaucouite		Muscovite
	Glaucouite		Halloysite		Pyrophyllite
	Graphite		Iddingsite		Steatite
2.26 - 2.30	Analcite		Kaolinite	2.76 - 2.78	Anorthite
	Glaucouite		Pyrophyllite		Clinocllore
2.30 - 2.34	Glaucouite	2.62 - 2.64	Chalcedony		Collophane
	Gypsum		Collophane		Glaucouite
2.34 - 2.36	Gibbsite		Cordierite		Iddingsite
	Glaucouite		Glaucouite		Muscovite
2.36 - 2.48	Glaucouite		Iddingsite		Pyrophyllite
2.48 - 2.50	Chrysotile		Kaolinite		Steatite
	Glaucouite		Oligoclase	2.78 - 2.80	Biotite
	Montmorillonite		Pyrophyllite		Collophane
		2.64 - 2.66	Collophane		Delessite
	Nontronite		Cordierite		Glaucouite
2.50 - 2.52	Chrysotile		Glaucouite		Iddingsite
	Glaucouite		Iddingsite		Muscovite
	Iddingsite		Oligoclase		Pyrophyllite
	Montmorillonite		Pyrophyllite		Steatite
			Quartz	2.80 - 2.82	Biotite
	Nontronite	2.66 - 2.68	Andesine		Collophane
2.52 - 2.54	Glaucouite		Collophane		Delessite
	Iddingsite		Cordierite		Dolomite
2.54 - 2.56	Chalcedony		Glaucouite		Iddingsite
	Glaucouite		Iddingsite		Lepidolite
	Iddingsite		Pyrophyllite		Muscovite
	Microcline		Quartz		Pyrophyllite
	Orthoclase	2.68 - 2.70	Andesine	2.82 - 2.84	Biotite
2.56 - 2.58	Anorthoclase		Collophane		Collophane
	Chalcedony		Glaucouite		Dolomite
	Cordierite		Iddingsite		Iddingsite
	Glaucouite		Labradorite		Lepidolite
	Iddingsite		Penninite		Muscovite
	Orthoclase		Pyrophyllite		Pyrophyllite
2.58 - 2.60	Anorthoclase	2.70 - 2.72	Calcite	2.84 - 2.86	Biotite
	Antigorite		Collophane		Collophane
	Beidellite		Glaucouite		Dolomite
	Chalcedony		Iddingsite		Fuchsite
	Cordierite		Labradorite		Lepidolite
	Dickite		Penninite		Muscovite
	Glaucouite		Pyrophyllite		Phlogopite
	Halloysite		Steatite		Pyrophyllite
	Iddingsite	2.72 - 2.74	Bytownite	2.86 - 2.88	Biotite
	Pyrophyllite		Collophane		Collophane
2.60 - 2.62	Albite		Glaucouite		Dolomite
	Antigorite		Iddingsite		Fuchsite

2-86 - 2-88	Lepidolite Muscovite Phlogopite Pyrophyllite	3-10 - 3-12	Hornblende Humite Lawsonite Lepidomelane Phlogopite Spodumene Tourmaline Tremolite	3-22 - 3-24	Hornblende Humite Phlogopite Sillimanite Tremolite
2-88 - 2-90	Biotite Collophane Dolomite Lepidolite Muscovite Phlogopite Pyrophyllite Wollastonite	3-12 - 3-16	Actinolite Andalusite Biotite Crossite Diopside Enstatite Glaucophane Hornblende Humite Phlogopite Spodumene Tourmaline Tremolite	3-24 - 3-26	Actinolite Augite Axinite Chloritoid Diopside Enstatite Epidote Hornblende Humite Phlogopite Sillimanite Tremolite Zoisite
2-90 - 2-92	Anhydrite Biotite Collophane Muscovite Phlogopite Wollastonite	3-16 - 3-18	Actinolite Andalusite Apatite Basaltine Crossite Diopside Enstatite Fluorite Hornblende Humite Phlogopite Spodumene Tourmaline Tremolite	3-26 - 3-28	Actinolite Augite Axinite Chloritoid Diopside Dumortierite Enstatite Epidote Hornblende Humite Olivine Phlogopite Tremolite Zoisite
2-92 - 2-94	Anhydrite Aragonite Biotite Muscovite Phlogopite				
2-94 - 2-96	Anhydrite Ankerite Aragonite Biotite Magnesite Muscovite Phlogopite				
2-96 - 2-98	Anhydrite Ankerite Biotite Muscovite Phlogopite				
2-98 - 3-00	Anhydrite Biotite Muscovite Phlogopite Tourmaline	3-18 - 3-20	Actinolite Andalusite Apatite Basaltine Diopside Enstatite Fluorite Hornblende Humite Phlogopite Spodumene Tourmaline Tremolite	3-28 - 3-30	Actinolite Augite Axinite Chloritoid Diopside Dumortierite Enstatite Epidote Hornblende Humite Olivine Ottrelite Phlogopite Tremolite Zoisite
3-00 - 3-08	Actinolite Biotite Glaucophane Hornblende Phlogopite Tourmaline Tremolite				
3-08 - 3-10	Actinolite Biotite Glaucophane Hornblende Lawsonite Lepidomelane Phlogopite Tourmaline Tremolite	3-20 - 3-22	Actinolite Apatite Augite Diopside Enstatite Hornblende Humite Phlogopite Tremolite	3-30 - 3-32	Augite Chloritoid Diopside Dumortierite Epidote Hypersthene Olivine Ottrelite Zoisite
3-10 - 3-12	Actinolite Andalusite Biotite Diopside Enstatite Glaucophane	3-22 - 3-24	Actinolite Apatite Augite Diopside Enstatite	3-32 - 3-34	Arfvedsonite Augite Chloritoid Diopside Dumortierite Epidote

3-32 - 3-34	Hypersthene Olivine Zoisite	3-44 - 3-46	Piedmontite Riebeckite Titanite Vesuvianite	3-66 - 3-68	Leucoxene Staurolite
3-34 - 3-36	Arfvedsonite Augite Chloritoid Clinzoisite Diopside Dumortierite Epidote Hypersthene Olivine Vesuvianite Zoisite	3-46 - 3-48	Augite Chloritoid Diaspore Epidote Hypersthene Piedmontite Titanite	3-68 - 3-72	Leucoxene Melanite Staurolite Strontianite
3-36 - 3-38	Arfvedsonite Augite Chloritoid Clinzoisite Diopside Epidote Hypersthene Olivine Vesuvianite Uvarovite Zoisite	3-48 - 3-50	Augite Chloritoid Diaspore Epidote Grossularite Hypersthene Piedmontite Titanite	3-72 - 3-74	Leucoxene Staurolite
3-38 - 3-40	Arfvedsonite Augite Chloritoid Diopside Epidote Hypersthene Olivine Vesuvianite Uvarovite Zoisite	3-50 - 3-52	Ægirine Augite Chloritoid Diamond Grossularite Leucoxene Pyrope Titanite	3-74 - 3-76	Enigmatite Leucoxene Staurolite
3-40 - 3-42	Arfvedsonite Augite Chloritoid Diaspore Diopside Epidote Grossularite Hypersthene Titanite Uvarovite Vesuvianite	3-52 - 3-54	Ægirine Augite Chloritoid Diamond Grossularite Leucoxene Titanite	3-76 - 3-78	Andradite Enigmatite Leucoxene Siderite Staurolite
3-42 - 3-44	Arfvedsonite Augite Barkevicite Chloritoid Diaspore Epidote Grossularite Hypersthene Riebeckite Titanite Vesuvianite	3-54 - 3-56	Ægirine Augite Chloritoid Grossularite Leucoxene Titanite	3-78 - 3-80	Andradite Enigmatite Leucoxene Limonite Siderite Spessartite
3-44 - 3-46	Arfvedsonite Augite Chloritoid Diaspore Epidote Grossularite Hypersthene	3-56 - 3-58	Augite Chloritoid Grossularite Leucoxene Topaz	3-80 - 3-82	Enigmatite Leucoxene Limonite Siderite Spessartite
		3-58 - 3-60	Augite Grossularite Leucoxene Periclase Spinel Topaz	3-82 - 3-84	Anatase Ceylonite Enigmatite Leucoxene Siderite Spessartite
		3-60 - 3-62	Kyanite Leucoxene Periclase Spinel	3-84 - 3-86	Anatase Ceylonite Enigmatite Leucoxene Siderite Spessartite
		3-62 - 3-64	Kyanite Leucoxene	3-86 - 3-88	Anatase Brookite Leucoxene Siderite Spessartite
		3-64 - 3-66	Benitoite Kyanite Leucoxene Staurolite	3-88 - 3-90	Anatase Brookite Hercynite Leucoxene Siderite Spessartite
		3-66 - 3-68	Kyanite	3-90 - 3-94	Anatase Brookite Hercynite Leucoxene Spessartite
				3-94 - 3-96	Anatase Brookite Celestite Corundum Leucoxene Spessartite
				3-96 - 3-98	Brookite

3.96 - 3.98	Corundum	4.18 - 4.20	Almandite	4.52 - 4.58	Chromite
	Celestite		Goethite		Ilmenite
	Leucoxene		Leucoxene		Pyrrhotite
	Spessartite		Psilomelane		Xenotime
3.98 - 4.00	Brookite		Rutile		Zircon
	Corundum		Spessartite	4.58 - 4.60	Ilmenite
	Leucoxene	4.20 - 4.22	Almandite		Pyrrhotite
	Spessartite		Goethite		Xenotime
4.00 - 4.06	Brookite		Leucoxene		Zircon
	Corundum		Psilomelane	4.60 - 4.70	Ilmenite
	Goethite		Rutile		Pyrrhotite
	Leucoxene		Spessartite		Zircon
	Spessartite	4.22 - 4.26	Almandite	4.70 - 4.74	Ilmenite
	Sphalerite		Goethite		Pyrrhotite
4.06 - 4.08	Brookite		Leucoxene	4.74 - 4.76	Ilmenite
	Corundum		Rutile		Pyrolusite
	Goethite		Spessartite		Pyrrhotite
	Leucoxene	4.26 - 4.28	Almandite	4.76 - 4.78	Ilmenite
	Picotite		Goethite		Pyrrhotite
	Spessartite		Leucoxene	4.78 - 4.80	Ilmenite
	Sphalerite	4.28 - 4.30	Almandite		Marcasite
4.08 - 4.10	Corundum		Fayalite		Pyrite
	Goethite		Goethite		Pyrrhotite
	Leucoxene		Leucoxene	4.80 - 4.90	Ilmenite
	Picotite	4.30 - 4.32	Fayalite		Pyrite
	Spessartite		Goethite	4.90 - 5.00	Ilmenite
	Sphalerite		Leucoxene		Monazite
4.10 - 4.14	Almandite	4.32 - 4.40	Chromite		Pyrite
	Goethite		Goethite	5.00 - 5.10	Monazite
	Leucoxene		Leucoxene		Pyrite
	Spessartite		Xenotime	5.10 - 5.18	Magnetite
4.14 - 4.16	Allanite	4.40 - 4.50	Barite		Monazite
	Almandite		Chromite	5.18 - 5.22	Hematite
	Goethite		Leucoxene		Monazite
	Leucoxene		Xenotime	5.22 - 5.30	Monazite
	Spessartite	4.50 - 4.52	Barite	6.80 - 7.10	Cassiterite
4.16 - 4.18	Almandite		Chromite	7.20 - 7.40	Wolframite
	Goethite		Ilmenite	7.40 - 7.50	Galena
	Leucoxene		Xenotime		Wolframite
	Rutile		Zircon	7.50 - 7.60	Galena
	Spessartite				

APPENDIX V.

Minerals arranged according to their intermediate indices of refraction.

1.406	Opal	1.59	Collophane	1.680	Diopside
1.43	Opal	1.590	Nontronite	1.681	Olivine
1.434	Fluorite		Muscovite	1.682	Aragonite
1.440	Opal	1.592	Hiddenite	1.683	Basaltine
1.46	Opal	1.594	Fuchsite	1.685	Axinite
1.470	Halloysite	1.597	Cordierite	1.686	Dumortierite
1.47	Allophane	1.598	Lepidolite	1.687	Tourmaline
1.487	Analcite	1.599	Muscovite		Riebeckite
1.49	Allophane	1.600	Nontronite	1.689	Hypersthene
1.502	Antigorite		Biotite	1.691	Hornblende
1.512	Chrysotile		Beidellite	1.695	Riebeckite
1.52	Halloysite	1.61	Allanite	1.698	Ankerite
1.523	Gypsum		Nontronite		Tourmaline
1.524	Orthoclase	1.611	Muscovite	1.70	Arfvedsonite
1.525	Anorthoclase	1.616	Tremolite	1.701	Olivine
1.526	Microcline	1.618	Glaucosite	1.702	Hypersthene
	Montmorillonite	1.619	Delessite		Zoisite
1.529	Albite	1.62	Nontronite	1.703	Zoisite
1.537	Chalcedony	1.620	Topaz	1.704	Augite
	Beidellite	1.623	Tremolite	1.705	Pyrope
1.538	Cordierite	1.624	Celestite	1.706	Olivine
1.542	Halloysite	1.627	Actinolite	1.707	Barkevicite
1.543	Oligoclase	1.628	Glaucosite		Sapphire
1.544	Quartz	1.629	Wollastonite	1.708	Vesuvianite
1.547	Cordierite	1.630	Chlorite	1.715	Iddingsite
1.550	Chrysotile	1.63	Collophane	1.716	Ankerite
1.553	Andesine		Biotite	1.717	Clinozoisite
1.555	Lepidolite	1.632	Humite	1.718	Spinel
	Halloysite	1.637	Chlorite	1.719	Epidote
1.558	Serpentine		Barite	1.72	Allanite
1.561	Lepidolite	1.638	Lepidomelane	1.720	Kyanite
	Phlogopite		Glaucophane		Spinel
1.562	Chlorite	1.639	Andalusite		Clinozoisite
	Cordierite	1.642	Hornblende	1.721	Xenotime
1.563	Labradorite	1.643	Humite	1.722	Diaspore
	Dickite	1.645	Nontronite		Chloritoid
1.565	Montmorillonite	1.648	Biotite	1.725	Hornblende
	Kaolinite	1.649	Apatite	1.726	Magnesite
1.566	Gibbsite	1.650	Iddingsite	1.728	Hypersthene
1.568	Collophane	1.652	Tourmaline	1.729	Clinozoisite
1.570	Antigorite	1.653	Enstatite	1.73	Piedmontite
1.572	Chlorite	1.658	Calcite		Ottrelite
	Beidellite	1.660	Chlorite		Augite
	Bytownite		Sillimanite	1.736	Pericase
1.574	Biotite	1.666	Hornblende		Grossularite
	Phlogopite		Spodumene	1.739	Allanite
1.575	Anhydrite	1.667	Strontianite	1.741	Staurolite
1.576	Penninite	1.669	Enstatite	1.742	Pyrope
1.579	Penninite	1.670	Olivine		Epidote
1.581	Chlorite		Crossite	1.749	Ankerite
	Muscovite	1.671	Diopside	1.75	Ceylonite
1.582	Beidellite	1.673	Hornblende		Spinel
1.584	Anorthite	1.674	Lawsonite	1.757	Benitoite
1.585	Nontronite	1.676	Biotite		Piedmontite
1.586	Clinocllore	1.678	Hypersthene	1.76	Ceylonite
1.588	Pyrophyllite	1.68	Allanite	1.763	Epidote
1.589	Steatite		Dolomite	1.768	Almandite

1-768	Corundum	1-849	Siderite	2-15	Goethite
1-777	Ceylonite	1-855	Siderite	2-16	Chromite
1-778	Almandite	1-857	Andradite	2-22	Goethite
1-78	Ceylonite	1-864	Fayalite	2-29	Goethite
1-782	Piedmontite	1-875	Siderite	2-32	Wolframite
1-79	Ceylonite	1-895	Andradite	2-35	Goethite
1-799	Ægirine	1-907	Titanite	2-36	Wolframite
1-800	Spessartite	1-923	Zircon	2-37	Sphalerite
1-80	Enigmatite	1-926	Zircon	2-419	Diamond
"	Hercynite	1-936	Zircon	2-42	Magnetite
1-801	Almandite	1-94	Melanite	2-47	Sphalerite
"	Monazite	1-960	Zircon	2-554	Anatase
1-811	Spessartite	1-997	Cassiterite	2-586	Brookite
1-814	Spessartite	2-00	Graphite	2-616	Rutile
1-83	Iddingsite	2-037	Sulphur	3-01	Hematite
1-830	Almandite	2-05	Picotite	3-22	Hematite
"	Siderite	2-06	Limonite	>2-72	Ilmenite
1-838	Uvarovite	2-07	Chromite		

APPENDIX VI.

Isotropic Minerals.

Allophane
Almandite
Analcite
Andradite
Ceylonite
Chromite
Collophane
Diamond

Fluorite
Galena
Grossularite
Halloysite
Hercynite
Melanite
Opal
Periclase

Picotite
Pyrope
Spessartite
Sphalerite
Spinel
Uvarovite

APPENDIX VII.

Minerals arranged in order of birefringence.

0-001	...	Gypsum	0-023	...	Glauconite
0-003	...	Penninite	"	...	Nontronite
0-005	...	Apatite	0-024	...	Allanite
"	...	Clinocllore	"	-0-026	Glauconite
"	...	Kaolinite	"	...	Montmorillonite
0-006	...	Cordierite	0-027	...	Actinolite
"	...	Dickite	"	...	Glauconite
"	...	Enigmatite	"	...	Tremolite
"	...	Muscovite	0-028	...	Epidote
"	...	Riebeckite	"	-0-029	Glauconite
"	...	Sapphire	0-030	...	Diopside
0-007	...	Andesine	"	-0-031	Glauconite
"	...	Chalcedony	"	...	Humite
0-008	...	Anorthoclase	0-032	...	Glauconite
"	...	Corundum	0-034	...	Lawsonite
"	...	Enstatite	0-036	...	Olivine
"	...	Microcline	0-040	...	Fuchsite
"	...	Oligoclase	"	...	Tourmaline
"	...	Orthoclase	0-042	...	Beidellite
"	...	Topaz	"	...	Fayalite
"	...	Vesuvianite	0-043	...	Augite
0-009	...	Andalusite	"	...	Muscovite
"	...	Celestite	0-044	...	Anhydrite
"	...	Labradorite	0-045	...	Ægirine
"	...	Quartz	0-047	...	Benitoite
0-010	...	Axinite	"	...	Lepidolite
"	...	Bytownite	"	...	Phlogopite
"	...	Clinocllore	0-048	...	Laspoire
"	...	Clinozoisite	"	...	Pyrophyllite
"	...	Crossite	0-049	...	Monazite
"	...	Ottrelite	0-050	...	Steatite
"	...	Staurolite	0-055	...	Zircon
0-011	...	Albite	0-061	...	Anatase
"	...	Chloritoid	0-064	...	Biotite
"	...	Dumortierite	0-074	...	Goethite
"	...	Hiddenite	0-082	...	Piedmontite
0-012	...	Anorthite	0-087	...	Iddingsite
"	...	Arfvedsonite	0-095	...	Xenotime
"	...	Barite	0-096	...	Cassiterite
0-013	...	Hypersthene	0-118	...	Lepidomelane
0-014	...	Chrysotile	0-134	...	Titanite
"	...	Delessite	0-147	...	Strontianite
"	...	Wollastonite	0-155	...	Aragonite
0-016	...	Hornblende	0-158	...	Brookite
"	...	Kyanite	0-16	...	Wolframite
"	...	Spodumene	0-172	...	Calcite
0-017	...	Glaucophanes	0-180	...	Ankerite
0-018-0-020	...	Glauconite	0-181	...	Dolomite
"	...	Zoisite	0-190	...	Ankerite
0-021	...	Antigorite	0-191	...	Magnesite
"	...	Barkevicite	0-242	...	Siderite
"	...	Gibbsite	0-28	...	Hematite
"	-0-022	Glauconite	0-287	...	Rutile
"	...	Sillimanite	0-288	...	Sulphur
0-023	...	Basaltine			

APPENDIX VIII.

Minerals arranged in order of optical sign.

UNIAXIAL, POSITIVE.

Benitoite
Cassiterite

Quartz
Rutile

Xenotime
Zircon

UNIAXIAL, NEGATIVE.

Anatase
Ankerite
Apatite
Calcite

Corundum
Dolomite
Graphite
Hematite
Lepidomelane

Magnesite
Siderite
Tourmaline
Vesuvianite

BIAXIAL, POSITIVE.

Albite
Andesine
Anhydrite
Augite
Barite
Brookite
Celestite
Chalcedony
Chloritoid
Chrysotile
Clinocllore
Clinzoisite

Diaspore
Dickite
Diopside
Enigmatite
Enstatite
Gibbsite
Gypsum
Humite
Iddingsite
Labradorite
Lawsonite
Monazite

Olivine
Ottrelite
Penninite
Piedmontite
Sillimanite
Spodumene
Staurolite
Sulphur
Titanite
Topaz
Wolframite
Zoisite

BIAXIAL, NEGATIVE.

Actinolite
Ægirine
Allanite
Analcite
Andalusite
Anorthite
Anorthoclase
Antigorite
Aragonite
Arfvedsonite
Axinite
Barkevicite
Basaltine
Beidellite
Biotite
Bytownite

Clinocllore
Clinzoisite
Cordierite
Crossite
Delessite
Dumortierite
Epidote
Fayalite
Fuchsite
Glaucosite
Glaucophane
Goethite
Hornblende
Hypersthene
Iddingsite
Kaolinite
Kyanite

Lepidolite
Lepidomelane
Microcline
Montmorillonite.
Muscovite
Nontronite
Oligoclase
Olivine
Orthoclase
Phlogopite
Pyrophyllite
Riebeckite
Steatite
Strontianite
Tremolite
Wollastonite

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SUBJECT INDEX.

Page numbers printed in bold type indicate either the main reference to the subject or alternatively, in cases where no other reference is given, that a complete section (as opposed to passing reference) is devoted to the subject.

A

- Absorption spectra, **142**
- Abyssal clay, 360, **382**
 - ooze, 360
 - calcareous, **388**
 - siliceous, **402**
- Accessory minerals, contamination, **476**
 - correlation of isolated plutonic outcrops by, 476
 - in igneous rocks, **474**
 - normal, 476
 - pneumatolytic, 476
 - secondary, 476
- Acetylene tetrachloride, dielectric constant of, 129
- Acid digest, of samples for heavy mineral investigation, **63**
 - solubility, determination of, **192**
- Actinolite, **229**
 - electrical properties of, 127
 - frequency, 499
 - geochemical notes on, 500
 - identified in soils, 527
 - magnetic properties of, 126
 - mode of occurrence, 499
 - stability, 499
- Adobe, American, 381
- Ægirine, **230**
 - frequency, 499
 - geochemical notes on, 500
 - mode of occurrence, 499
 - stability, 499
- Æolian clay, 360, **381**
- Agate (variety of chalcedony, *q.v.*)
 - frequency, 499
 - geochemical notes on, 500
 - mode of occurrence, 499
 - stability, 499
- Aggregate, definition of, 553
- Aggregates, cloudy, elimination from heavy residues, **78**
 - composite, identification, of, **188**
- Aggregates, shimmer, **187**
 - weight per cubic foot of fine, **212**
 - coarse, **212**
- Air-Bubbles, exclusion from microscope slides, 56
 - mounting, of foraminifera, 57
 - of thin sections, 41
- Albertite, 415
- Albite, **231**
 - frequency, 499
 - geochemical notes on, 500
 - identified in soils, 527
 - mode of occurrence, 499
 - stability, 499
- Algal limestone, 394
- Alkaline digest, of samples for heavy mineral investigation, **63**
- Allanite, **232**
 - frequency, 499
 - geochemical notes on, 500
 - mode of occurrence, 499
 - stability, 499
- "Alite," 559
- Allophane, **232**
 - frequency, 499
 - geochemical notes on, 500
 - mode of occurrence, 499
 - stability, 499
- Alluvial mining, application of sedimentary petrography to, 7
- Almandite, **233**
 - frequency, 499
 - geochemical notes on, 500
 - mode of occurrence, 499
 - stability, 499
- Alteration products, minerals masked by, **188**
- Aluminous silicates, 377, 380
- Amber, behaviour to X-rays, 134
- Amblygonite, identified in soils, 528
- Amorphous minerals, **227, 604**
- Amphibole group, 229, 246, 250, 273, 289, 297, 333, 349

- Amyl alcohol**, dielectric constant of, 129
- Analcite**, 234
- frequency, 499
 - geochemical notes on, 500
 - mode of occurrence, 499
 - stability, 499
- Analyser**, anastigmatic, 154
- mounted over ocular, 155
 - synchronous rotation with polariser, 155
- Anatase**, 235
- electrical properties of, 127
 - frequency, 499
 - geochemical notes on, 501
 - identified in soils, 528
 - mode of occurrence, 499
 - stability, 499
- Andalusite**, 236
- behaviour to X-rays, 134
 - frequency, 499
 - geochemical notes on, 501
 - identified in soils, 527
 - indicative of climatic conditions of deposition, 496
 - mode of occurrence, 499
 - stability, 499
- Andesine**, 238
- frequency, 499
 - geochemical notes on, 501
 - identified in soils, 527
 - mode of occurrence, 499
 - stability, 499
- Andradite**, 238
- behaviour to X-rays, 134
 - frequency, 499
 - geochemical notes on, 501
 - mode of occurrence, 499
 - stability, 499
- Andrews kinetic elutriator**, 88
- modifications in standard instrument, 98
- Anhydrite**, 239
- elimination from heavy residues, 76
 - frequency, 499
 - geochemical notes on, 501
 - mode of occurrence, 499
 - stability, 499
- Aniline**, dielectric constant of, 129
- Ankerite**, 240
- frequency, 499
 - geochemical notes on, 501
 - mode of occurrence, 499
 - stability, 499
- Anorthic system (triclinic)**, 227, 604
- Anorthite**, 241
- frequency, 499
 - geochemical notes on, 501
 - identified in soils, 527
- Anorthite**, mode of occurrence, 499
- stability, 499
- Anorthoclase**, 241
- frequency, 499
 - geochemical notes on, 501
 - mode of occurrence, 499
 - stability, 499
- Anthracite**, 360, 400
- Antigorite**, 242
- frequency, 499
 - geochemical notes on, 502
 - mode of occurrence, 499
 - stability, 499
- Apatite**, 243
- behaviour to X-rays, 134
 - frequency, 499
 - geochemical notes on, 502
 - identified in soils, 527
 - mode of occurrence, 499
 - stability, 499
- Aragonite**, 245
- frequency, 499
 - geochemical notes on, 502
 - mode of occurrence, 499
 - stability, 499
- Archæan gneiss**, 494
- Arenaceous deposits**, 360, 385
- Arfvedsonite**, 246
- frequency, 499
 - geochemical notes on, 502
 - mode of occurrence, 499
 - stability, 499
- Argillaceous deposits**, 360, 374
- separation of heavy minerals from, 78
- Arkose**, 360, 380
- trade name for, 574
- A.S.T.M. sieves**, 86, 88
- Asbestos**, 349
- industry, silicosis scheme, 585
- Ashdown sand**, mineral residue from, 485
- Ashton zone**, Los Angeles Basin, 480
- Asphalt**, 360, 414
- compressed rock, 576
 - distinction between natural and synthetic, 546
 - native, 546
 - rolled, 575
 - soluble bitumen' determination of natural, 195
 - synthetic, 542
- Asphaltic Bitumen**, 360, 414
- soluble bitumen determination of, 195
- Asphalt industry**, sedimentary petrology applied to, 541
- Assemblages**, character of heavy mineral, 461
- Atterberg scale**, 530

Auger-drill samples, 17
Augite, 248
 — electrical properties of, 127
 — frequency, 499
 — geochemical notes on, 502
 — identified in soils, 527
 — magnetic properties of, 126
 — mode of occurrence, 499
 — stability, 499
Axinite, 248
 — frequency, 499
 — geochemical notes on, 502
 — identified in soils, 527
 — index mineral, 492
 — mode of occurrence, 499
 — stability, 499
 Azurite, identified in soils, 528

B

 Bagshot beds, of Essex, 8
 — — — — — mineral content
 of, 485
 Bailer samples (cable tool system), 18
 Ball clay, 561
 Ballast, definition of, 553
 — Sand and Allied Trades Association, 553
 Barbados earth, 403
Barite, 248
 — elimination from heavy residues,
 76
 — frequency, 499
 — geochemical notes on, 502
 — identified in soils, 528
 — in limestone, 546
 — mode of occurrence, 499
 — stability, 499
 Bar test, of sands, 196
Barkevicite, 250
 — frequency, 499
 — geochemical notes on, 502
 — mode of occurrence, 499
 — stability, 499
 Bartlesville sand, physical properties
 of minerals in, 484
 Baryto-calcite, fluorescence of, 144
Basaltic hornblende, 250
Basaltine, 250
 — frequency, 499
 — geochemical notes on, 502
 — mode of occurrence, 499
 — stability, 499
 "Base bed" limestone, 548
Bastite, 251
 — frequency, 499
 — geochemical notes on, 503
 — mode of occurrence, 499
 — stability, 499
Bauxite, 561
 Becke's "white line" method of R.L.
 determination, 168

Bedded iron ores, 3, 361, 423
 Bedding, in samples, 34
Beidellite, 251
 — frequency, 499
 — geochemical notes on, 503
 — lattice type of, 525
 — mode of occurrence, 499
 — stability, 499
 Belemnite marl, 400
 Belgium, evolution of sedimentary
 petrography in, 9
 "Belite," 559
Benitoite, 252
 — frequency, 499
 — geochemical notes on, 503
 — mode of occurrence, 499
 — stability, 499
 Bentonite, 375, 383, 384
 Benzene, dielectric constant of, 129
 Bertrand lens, 152
 Beryl, behaviour to X-rays, 134
 — fluorescence of, 144
Biaxial minerals, 175
Bibliography, general, 615
 — soil, 536
Biotite, 253
 — electrical properties of, 127
 — frequency, 499
 — geochemical notes on, 503
 — identified in soils, 527
 — magnetic properties of, 126
 — mode of occurrence, 499
 — stability, 499
 Birefringence (see also under individual minerals), of rock minerals,
 168, 223
 —, minerals arranged in order of,
 613
Bit-samples, 18
Bitumen, asphaltic, 360, 414
 — extraction of mineral matter
 from, 193
 — recovery of, 546
 — soluble, determination of, 195
 — ultra-violet fluorescence of, 145
Bituminous impregnated rocks, 360, 414
 — — — — — separation of heavy
 minerals from, 68, 80
 Blackband ironstone, 423
 Blende, dielectric constant of, 129
 "Bog-head Cannel," 412
 Bog iron ore, 361, 425
 Bolsa zone, Los Angeles Basin, 480
 Bone breccias, 418
Borates, 361, 430
 Borehole samples, examination of, 594
 Boryslaw oilfield, samples from, 483
 Boulder, definition of, 553
Boxstones, 424
Breccia, 360, 368

- Breccia, trade name for, 574
 Brockrams, the, 365
 Bromoform, recovery of, 52
 — separation of heavy minerals, 80, 83
 — — — apparatus for, 83
 — — — funnel battery for, 84
 Bronzite (variety of enstatite, *q.v.*)
 — frequency, 499
 — mode of occurrence, 499
 — stability, 499
 Brookite, 284
 — behaviour to X-rays, 134
 — electrical properties of, 127
 — frequency, 499
 — geochemical notes on, 503
 — interference figure of, 256
 — mode of occurrence, 499
 — stability, 499
 British standard sieves, 86, 88
 Brittany, residual decomposed igneous material of, 9
 Bryozoa limestone, 394
 Building construction, sedimentary petrology applied to, 541
 — technology, sedimentary petrography applied to, 547
 Bunter pebble beds, of the Midlands, 5, 492
 — — — of the West of England, 5, 494
 — — — of the West of England, shimmer aggregates, 188
 Bytownite, 257
 — frequency, 499
 — geochemical notes on, 503
 — identified in soils, 528
 — mode of occurrence, 499
 — stability, 499

C

- Cable tool system of drilling, 18
 Calcareo-argillaceous rocks, 360, 388
 Calcareous rocks, of chemical origin, 361, 421
 — — — of organic origin, 360, 391
 — — — separation of heavy minerals from, 77
 — shale, 360, 388
 Calcite, 287, 361, 421
 — dielectric constant of, 129
 — frequency, 499
 — geochemical notes on, 503
 — identification by fluorescence, 143
 — identified in soils, 527
 — mode of occurrence, 499
 — stability, 499
 Calc-sinter, 421
 Calc-tufa, 421
 Calcium carbonate, 361, 421

- Caliche deposits, 430
 Cambridgeshire sands, mineralogy of, 6
 Campina district, Rumania, samples from, 481
 Canada balsam, as a mountant, 37, 40
 Canadian geological survey, 8
 Cannel coal, 360, 412
 Carbon arc cathode layer method of spectrum analysis, 141
 — disulphide, matter insoluble in, in asphalts and asphaltic bitumens, 195
 — — — dielectric constant of, 129
 Carbonaceous rocks, 360, 406
 — — — separation of heavy minerals from, 77
 Carboniferous limestone, use in mastic asphalt, 544
 — — — fluorite as indicator of, 545
 — — — of Matlock (Derbyshire), 545
 — — — of Mendips, 549
 Cassiterite, 288
 — dielectric constant of, 129
 — electrical properties of, 127
 — frequency, 499
 — geochemical notes on, 503
 — identified in soils, 528
 — index mineral, 492
 — magnetic properties of, 126
 — mode of occurrence, 499
 — stability, 499
 Cedar oil, as mountant for sand grains, 56
 Celestite, 280
 — frequency, 499
 — geochemical notes on, 503
 — identification by fluorescence, 143
 — mode of occurrence, 499
 — stability, 499
 "Celite," 559
 Cement, rocks for manufacture of, 551
 — stone, 388, 395, 423
 — technology, 557
 Centrifuge methods of heavy mineral separation, 87
 — — — applied to native asphalts, 67
 — — — applied to rock powders with small H.R., 67
 — — — applied to sediments of low grain size, 67
 — — — with heavy liquid, 69
 — — — of particle size classification, 108
 — — — data and calculations from, 111
 — — — formulæ for, 109
 — — — standard conditions for,

- Ceramics, sedimentary petrography applied to, 580**
Ceylonite, 280
 — frequency, 499
 — geochemical notes on, 503
 — magnetic properties of, 126
 — mode of occurrence, 499
 — stability, 499
Chalcedony, 261
 — frequency, 499
 — geochemical notes on, 503
 — identified in soils, 528
 — mode of occurrence, 499
 — stability, 499
Chalcopyrite, in coal, 78
Chalk, 360, 390
 — for cement, 557
Chalybite, 336
Chamosite-siderite mudstones, 423
 "Cheesetaster," 17
Chemical composition (see also under individual minerals), 216
 — origin, rocks of, 419
Chert (variety of chalcedony, *q.v.*)
 — consolidated, 360, 401
 — frequency, 499
 — geochemical notes on, 504
 — mode of occurrence, 499
 — stability, 499
 — nucleus of composite grains, 186
 — trade name for, 574
Chiastolite (variety of andalusite, *q.v.*), 263
 — frequency, 449
 — geochemical notes on, 504
 — identified in soils, 528
 — mode of occurrence, 499
 — stability, 499
China clay, 384, 561
 — stone, 561
Chippings, definition of, 553
Chlorides, 361, 427
Chlorite, identified in soils, 527
 — magnetic properties of, 126
 — aggregates, 187
 — group, 242, 264, 273, 323
 "Chloritic matter," geochemical notes on, 504
Chloritoid, 265
 — frequency, 499
 — geochemical notes on, 504
 — index mineral, 492
 — magnetic properties of, 126
 — mode of occurrence, 499
 — stability, 499
Chloritoid-ottrelite group, 265, 323
Chloropal, 318
Chromite, 266
 — electrical properties of, 127
 — frequency, 499
 — geochemical notes on, 504
 — identified in soils, 528
Chromite, magnetic properties of, 126
 — mode of occurrence, 499
 — stability, 499
Chronologic and lithologic planes, transgression of, 488, 469
Chrysoberyl, behaviour to X-rays, 134
 — identified in soils, 528
Chrysolite, 319
Chrysotile, 267
 — frequency, 499
 — geochemical notes on, 504
 — mode of occurrence, 499
 — stability, 499
Cinnabar, in coal, 78
Clarain, 410
Classification of rock particles, 85
 — of sediments, 6
 — of sedimentary rocks, 360
 — of soils, 518
Clay, 360, 376
 — abyssal, 360, 382
 — æolian, 360, 381
 — ball, 561
 — china, 561
 — definition of, 553
 — detrital minerals of, 5
 — extraction of heavy minerals from, 47
 — for cement manufacture, 557
 — ironstone, 423
 — limiting dimensions of, 85
 — residual, 360, 384
 — volcanic, 360, 383
Cleavage, in samples, 34
 — of minerals, 216
Climatic conditions of deposition of sediments, feldspar grains as indicators of, 496
Clinochlore, 268
 — frequency, 499
 — geochemical notes on, 504
 — mode of occurrence, 499
 — stability, 499
Clinzoisite, 269
 — frequency, 499
 — geochemical notes on, 504
 — mode of occurrence, 499
 — stability, 499
Coal, 360, 400
 — cannel, 360, 412
Coalinga, California, samples from, 487
Cobble, definition of, 554
Cohesiveness test, of sands, 106
Collophane, 269
 — frequency, 499
 — geochemical notes on, 504
 — mode of occurrence, 499
 — stability, 499
Colour of minerals, 223
 — of soils, 532

- Colour chart, National Research Council, 32
 ——— Ridgway, 32
 Coloured light, use in petrographic work, 188
 Colour systems, employed in megascopic examination of samples, 32
 Compensators, for petrological microscope, 163
 Composition (inorganic constituents) of sediments, 33
 Concentration of heavy minerals, 50
 ——— bromoform, 50, 63
 ——— centrifuge methods of, 67
 ——— dielectric, 128
 ——— electromagnetic, 122
 ——— electrostatic, 126
 ——— filming, 131
 ——— flotation methods of, 130
 ——— from argillaceous rocks, 76
 ——— bituminous rocks, 80
 ——— calcareous rocks, 77
 ——— crushed rocks, 80
 ——— hand, 74
 ——— heavy liquids, 70
 ——— magnetic, 121
 ——— oil buoyancy, 131
 ——— panning, 65
 ——— simultaneous, of micro-organisms and heavy minerals, 58
 ——— single, of heavy minerals, 48, 50
 ——— vibratory, 130
 Concrete, aggregate for, 551
 Conductivity of minerals (see also under individual minerals), 127
 Conglomerate, 360, 362
 ——— trade name for, 574
 "Coning," 29
 Consolidated sediments, 358
 ——— petrography of, 358
 ——— thin section correlation of, 472
 Copper, identified in soils, 528
 Coprolites, 418
 Coral limestone, 394
 Cordierite, 270
 ——— frequency, 499
 ——— geochemical notes on, 504
 ——— identified in soils, 528
 ——— magnetic properties of, 126
 ——— mode of occurrence, 499
 ——— stability, 499
 Core-barrel, 20
 Core samples, 16, 19
 ——— contamination of, 20, 21
 ——— diamond drill, 21
 ——— treatment of before examination, 21
 Core-trays, 23
 ——— labelling of, 25
 Cornwall, correlation of isolated Tertiary deposits, 7
 Cornwall, Pliocene deposits of, 494
 ——— purple zircon in Eocene deposits of, 494
 Correlation of sediments, 431
 ——— by investigation of physical properties of minerals, 464, 478
 ——— of oil-sands, 483
 ——— thin section, of sediments, 472
 Corundum, 271
 ——— behaviour to X-rays, 134
 ——— frequency, 499
 ——— geochemical notes on, 505
 ——— identified in soils, 527
 ——— index mineral, 492
 ——— mode of occurrence, 499
 ——— stability, 499
 Cotteswold slate, 550
 Counting of minerals, 66, 481, 455
 ——— descriptive method, 456
 ——— quantitative method, 458
 ——— graphical method, 457
 Crackle breccia, 364
 Criminology, petrographic methods applied to, 584
 Crinoidal limestone, 394
 Crossite, 273
 ——— frequency, 499
 ——— geochemical notes on, 505
 ——— mode of occurrence, 499
 ——— stability, 499
 Crushed rocks, separation of heavy minerals from, 80
 Crustacean limestone, 394
 Crystallisation, amorphous, 227, 604
 ——— anorthic, 222, 227
 ——— cubic, 217, 225, 603
 ——— hexagonal, 219, 226, 603
 ——— isometric, 217, 225, 603
 ——— monoclinic, 222, 227, 603
 ——— orthorhombic, 221, 226, 603
 ——— rhombohedral, 220, 226, 603
 ——— systems of, 216, 603
 ——— tetragonal, 218, 226, 603
 ——— triclinic, 222, 227, 604
 ——— trigonal, 220, 226, 603
 Crystallographical features of minerals, 445
 Cubic system (isometric), 217, 225, 603
 Current-bedded formations, heavy minerals in, 466
 Cymatolite (see Spodumene)
 ——— frequency, 499
 ——— geochemical notes on, 505
 ——— mode of occurrence, 499
 ——— stability, 499

D

- Dacian Stage, samples from, 481
 Damourite, 347

Dark ground illumination, **180**
 Dartmoor granite, **8, 81**
 ——— accessory minerals in, **475**
 ——— "provenance" of accessory minerals of, **493**
 Delesse-Rosiwal linear method of estimating volume percentages, **198**
 Delessite, **273**
 ——— frequency, **499**
 ——— geochemical notes on, **505**
 ——— mode of occurrence, **499**
 ——— stability, **499**
 Density, determination of, **197**
 ——— C.G.S. system, **197**
 ——— F.P.S. system, **197**
 Detrital minerals, bearing on climatic conditions at time of deposition of sediments, **495**
 ——— concentration, **74**
 ——— frequency estimations of, **498, 499**
 ——— grade size of, **459**
 ——— lateral persistence of, **462**
 ——— of clays, **5**
 ——— of slates, **5**
 ——— prominent features of, **460**
 ——— reciprocal relationship between, **458**
 Devonshire, purple zircon in Eocene deposits of, **494**
 Diallage (variety of diopside, *q.v.*)
 ——— frequency, **499**
 ——— geochemical notes on, **505**
 ——— identified in soils, **527**
 ——— mode of occurrence, **499**
 ——— stability, **499**
 Diamond, **274**
 ——— behaviour to X-rays, **134**
 ——— fluorescence of, **144**
 ——— frequency, **499**
 ——— geochemical notes on, **505**
 ——— mode of occurrence, **499**
 ——— stability, **499**
 Diamond drill cores, **21**
 Diaspore, **278**
 ——— frequency, **499**
 ——— geochemical notes on, **505**
 ——— mode of occurrence, **499**
 ——— stability, **499**
 Diatomaceous earth, **403**
 Diatomite, **403**
 ——— for cement manufacture, **557**
 Dickite, **278**
 ——— frequency, **499**
 ——— geochemical notes on, **505**
 ——— lattice type of, **525**
 ——— mode of occurrence, **499**
 ——— stability, **499**
 Dielectric constants, table of, **129**
 ——— separation of minerals, **128**

Differentiation of formations, by index minerals, **483, 491**
 ——— sediments, by petrographic methods, **435, 478**
 Diopside, **277**
 ——— electrical properties of, **127**
 ——— frequency, **499**
 ——— geochemical notes on, **505**
 ——— identified in soils, **527**
 ——— index mineral, **492**
 ——— magnetic properties of, **126**
 ——— mode of occurrence, **499**
 ——— stability, **499**
 Displacement method of S.G. determination, **209**
 "Distributive province," **432, 436, 437, 490, 495**
 Dolomite, **278, 361, 422**
 ——— frequency, **499**
 ——— geochemical notes on, **505**
 ——— identified in soils, **527**
 ——— mode of occurrence, **499**
 ——— stability, **499**
 ——— for cement manufacture, **557**
 ——— trade name for, **574**
 Dolomitic limestone, **360, 395**
 Dorset, purple zircon in Eocene deposits of, **494**
 Drilling, hand instrument, **17**
 Drying samples, **31**
 Dumortierite, **279**
 ——— frequency, **499**
 ——— geochemical notes on, **506**
 ——— mode of occurrence, **499**
 ——— stability, **499**
 Durain, **409**
 Durham, Triassic sandstones of, **8**
 Dusts, action on lungs, **578**
 Dutch East Indies, petrology of soils of, **10**

E

East Anglia, glacial deposits of, **8**
 ——— Grinstead (Sussex), samples from, **484**
 Ebonite, dielectric constant of, **129**
 Echinoid limestone, **394**
 Eifel, **557**
 Elaterite, **415**
 "Electro-magnets," **123**
 Electro-magnetic separation, of heavy minerals, **122**
 Electrostatic properties of minerals **223** (see also under individual minerals)
 ——— separation of minerals, **126**
 Elgin sand, physical properties of minerals in, **484**
 Elutriation, **95**
 Elutriators, Andrews kinetic. **98**
 ——— air, **103**

Endostratic breccias, 364

Enigmatite, 280

- frequency, 499
- geochemical notes on, 506
- mode of occurrence, 499
- stability, 499

Enstatite, 281

- frequency, 499
- geochemical notes on, 506
- identified in soils, 527
- mode of occurrence, 499
- stability, 499

Epidote, 282

- behaviour to X-rays, 134
- frequency, 499
- geochemical notes on, 506
- group, 232, 260, 282, 326, 356
- identified in soils, 527
- index mineral, 483, 492
- magnetic properties of, 126
- mode of occurrence, 499
- stability, 499

Essex, Bagshot beds of, 8

Ethyl alcohol, dielectric constant of, 129

Ethylene dichloride, dielectric constant of, 129

Eucolite, identified in soils, 528

Europe, evolution of sedimentary petrography in, 9

Eye-piece micrometer, 160

F

"Falling velocities," principle of, applied to soils, 529

Fauk system samples, 21

Fayalite, 284

- frequency, 499
- geochemical notes on, 506
- mode of occurrence, 499
- stability, 499

"Felite," 559

Felspar, grains as indicators of climatic conditions prevalent at time of deposition of sediments, 496

- group, 241, 313, 321
- perthitic growths of, 187
- used in ceramic industry, 561

Fen peat, 407

Ferruginous rocks, of chemical origin, 361, 423

— of organic origin, 360, 408

Field-outcrops, stratigraphical differentiation of, 485

Filming methods of mineral concentration, 131

Fillers, 568

- weight per cubic foot of, 213
- definition of, 554
- tests of, 568

Filtration, sands for, 597

Fineness modulus, 84

Fireclay, 3, 360, 378

— used in ceramic industry, 561

Flagstones, 550

Flint (variety of chalcedony, *q.v.*)

- consolidated, 360, 481
- frequency, 499
- geochemical notes on, 506
- mode of occurrence, 499
- stability, 499
- used in ceramic industry, 561

Flotation methods of mineral concentration, 130

— filming, 131

— oil-buoyancy, 131

Flour, definition of, 554

"Fluorometer," Mayntz Petersen, 105

Fluorescence (ultra-violet) spectra, 142

— applied to bitumens, 145

Fluorite, 284

- as indicator of carboniferous limestone, 545
- dielectric constant of, 129
- frequency, 499
- geochemical notes on, 506
- identification of fluorescence, 144
- identified in soils, 527
- mode of occurrence, 499
- stability, 499

Fluorspar, used in ceramic industry, 561

Foraminifera, mounting of, 57

— presence of in samples, 34

Foraminiferal limestone, 394

Fossils, presence of, in samples, 33

Fracture, of minerals, 216 (see also under individual minerals)

France, evolution of sedimentary petrography in, 9

Freestone, 548

— St. Bees Head, 549

— Ancaster, 549

Frequency, estimations, 450, 455

- descriptive, 456
- graphical, 457
- quantitative, 458
- expression of, 453
- factor, 107

Friable rocks, impregnation of for microscopical examination, 42

— preparation of thin sections of, 40

Fuchsite, 285

- frequency, 499
- geochemical notes on, 506
- mode of occurrence, 499
- stability, 499

Fuller's Earth, 360, 380

Funnel-battery, for bromoform separation, 64

Fusain, 409

G

Galena, 286

- frequency, 499
- geochemical notes on, 506
- identified in soils, 528
- in coal, 78
- mode of occurrence, 499
- stability, 499

Ganister, 3, 360, 371

Garnet, 287

- behaviour to X-rays, 134
- fluorescence of, 145
- group, 233, 238, 292, 312, 329, 338, 350
- identified in soils, 527
- in the Oldhaven beds, 487
- magnetic properties of, 126

Gastaldite (see Glaucophane)

- frequency, 499
- geochemical notes on, 506
- mode of occurrence, 499
- stability, 499

Gauge, definition of, 554

Gelatin solution, as a mountant, 42

Geochemical notes, on minerals, 500

- significance, of detrital and authigenic species, 497

Geograms, 6, 7

Geographical cycle, modern interpretation of, 431

Geological survey, Canadian, 8

- Great Britain, 3
- Indian, 8

Germany, evolution of sedimentary petrography in, 10

Geyserite, 426

Gibbsite, 287

- frequency, 499
- geochemical notes on, 506
- identified in soils, 528
- mode of occurrence, 499
- stability, 499

Glacial deposits, of East Anglia, 8

Glance pitch, 415

Glass, identified in soils, 527

Glass-making, sands suitable for, 3, 572

Glass technology, 572

Glauberite, fluorescence of, 144

Glaucinite, 288

- as evidence of marine deposition of sediments, 498, 506
- frequency, 499
- geochemical notes on, 506
- identified in soils, 528
- magnetic properties of, 126
- mode of occurrence, 499
- stability, 499

Glaucophane, 289

- electrical properties of, 127

Glaucophane, frequency, 499

- geochemical notes on, 507
- identified in soils, 527
- mode of occurrence, 499
- stability, 499

Globigerina ooze, 399

Gneiss, Archæan, 494

Lewisian, 494

Goethite, 291

- frequency, 499
- geochemical notes on, 507
- identified in soils, 528
- mode of occurrence, 499
- stability, 499

Gold, in coal, 78

identified in soils, 528

Goose Creek, Texas, samples from, 480

Grade-size, of minerals, 489

Grahamite, 415

Grain "morphology," 448

size, 188

Granite, Ballycorus, 476

Bodmin Moor, 476

Dartmoor, 8, 81, 475, 493

Irish, 8

Lake District, 8

Scottish, 476, 494

monazite in, 494

Shap, 176

St. Austell, 476

Granitic and associated rocks, separation of heavy minerals from, 81

Granules, definition of, 554

Graphite, 291

- electrical properties of, 127
- frequency, 499
- geochemical notes on, 507
- identified in soils, 528
- mode of occurrence, 499
- stability, 499

Gravel, definition of, 554

Grauwacke, 360, 372

Graywacke, 360, 372

"Greywacke," 360, 372

trade name for, 574

Grinstead clay, 485

Grit, 360, 368

definition of, 555

Grossularite, 292

- behaviour to X-rays, 134
- frequency, 499
- geochemical notes on, 507
- mode of occurrence, 499
- stability, 499

Guano, 418

"Guiseley rock," 372

Gypsum, 283

- elimination from heavy residues, 76
- for cement manufacture, 557
- frequency, 499

Gypsum, geochemical notes on, 507

— identified in soils, 528

— mode of occurrence, 499

— plate, 163

— stability, 499

H

Halite, 427

Haloanhydrite, 240

Halloysite, 204

— frequency, 499

— geochemical notes on, 508

— lattice type of, 525

— mode of occurrence, 499

— stability, 499

Hand-drilling instruments, 17

Hardness, 216 (see also under individual minerals)

— minerals arranged in order of, 605

Heavy liquids, 10, 50, 70

— use with centrifuge, 69

Heavy mineral assemblages, influence of recognition of, on sedimentary petrography, 4

— information to be obtained from, 444

— character of total, 461

— concentration (see "Concentration" of heavy minerals)

— correlation, 453, 478

— counts, with and without panning, 451, 452

— "Heavy mineral" cult, influence on sedimentary petrology, 2

Heavy mineral separation (see "Concentration" of heavy minerals)

— minerals, apparatus for separation of, 53

— bromoform separation of, 54

— extraction from clays, 471

— limestones, 471

— saline deposits, 472

— identification of, 444

— impoverishment of, 471

— in current bedded formations, 466

— in native asphalts, 546

— percentage of, 108

— treatment of incoherent rocks for recovery of, 48

— residues, elimination of prolific minerals from, 75

— extraction from argillaceous rocks, 76

— bituminous impregnated rocks, 80

— calcareous rocks, 77

— carbonaceous rocks, 77

— crushed rocks, 80

— granitic and associated rocks, 81

Heavy residues, sampling, 54

Hematite, 295

— electrical properties of, 127

— frequency, 499

— geochemical notes on, 508

— identification of, 188

— identified in soils, 527

— magnetic properties of, 126

— mode of occurrence, 499

— stability, 499

Hercynite, 296

— frequency, 499

— geochemical notes on, 508

— mode of occurrence, 499

— stability, 499

Heulandite, identified in soils, 528

Hexagonal, system, 219, 226, 603

Hiddenite (variety of spodumene, *q.v.*)

— frequency, 499

— geochemical notes on, 508

— mode of occurrence, 499

— frequency, 499

Highway construction, sedimentary petrography applied to, 573

Hilger automatic quartz-glass spectrograph, 142

Hoggin, definition of, 555

Holland, evolution of sedimentary petrography in, 10

Hominy sand, physical properties of minerals in, 484

Hornblende, 297

— electrical properties of, 127

— frequency, 499

— geochemical notes on, 508

— identified in soils, 527

— in the Oldhaven beds, 487

— magnetic properties of, 126

— mode of occurrence, 499

— stability, 499

Hornblende, Basaltic, 250

Horseshoe magnets, for heavy mineral separation, 122

Humite, 298

— frequency, 499

— geochemical notes on, 508

— group, 298

— mode of occurrence, 499

— stability, 499

Huntington beach field, samples from, 479

Hyalite (see Opal)

— frequency, 499

— geochemical notes on, 508

— mode of occurrence, 499

— stability, 499

Hydrargillite, 287

Hydrometer, for checking specific gravity of bromoform, 51

Hydrostatic method of S.G. determination, 209

Hygroscopic moisture content, of oil
 impregnated rocks, **199**
 — of sediments, **199**

Hypersthene, 299

— electrical properties of, **127**
 — frequency, **499**
 — geochemical notes on, **508**
 — identified in soils, **527**
 — magnetic properties of, **126**
 — mode of occurrence, **499**
 — stability, **499**

I

Iddingsite, 301

— frequency, **499**
 — geochemical notes on, **508**
 — identified in soils, **527**
 — mode of occurrence, **499**
 — stability, **499**

Identification of minerals, petrographic
 methods applied to, **444**

Idocrase, 351 (see *Vesuvianite*)

Ightham stone, 367

Igneous rocks, accessory minerals in, 474

Ilmenite, 301

— electrical properties of, **127**
 — frequency, **499**
 — geochemical notes on, **508**
 — identified in soils, **527**
 — magnetic properties of, **126**
 — mode of occurrence, **499**
 — stability, **499**

Ilmenite-anatase, identification of, 186

Ilmenite-rutile, identification of, 186

Immersion media, for determination of R.I., 182

Impregnation, surface of friable rocks, 42, 46

— thorough, of friable rocks, **47**

Impregnated rocks, moisture content (hygroscopic) of, 199

— preparation of thin sections of, **40**

— extraction of mineral matter from, **193**

Inclusions, in minerals, 168

Incoherent rocks, treatment for recovery of heavy minerals etc., 48

Indexing, of samples, 25

Index minerals, 483, 491

Indian geological survey, 8

Indicolite, frequency, 499

— geochemical notes on, **509**

— mode of occurrence, **499**

— stability, **499**

Industrial maladies, sedimentary petrography applied to, 578

Infusorial earth, 403

Inorganic constituents of samples, 33

Institute of Mining and Metallurgy,
 sieves, **86, 88**

Interference colours, 170

— figure, **171**

Irish granites, 8

Iron-ore-quartz, identification of, 186

Iron ores, bedded, 3, 361, 423

— bog, **361, 425**

Ironstone, 574

Isometric system (cubic), 225, 603

Isotropic minerals, 612

Isotropism, 168

Italy, evolution of sedimentary petrography in, 10

J

Jade (see Nephrite)

Jamna sandstone, epidote as index mineral of, 483

Jasper (variety of chalcedony, *q.v.*)

— frequency, **499**

— geochemical notes on, **509**

— mode of occurrence, **499**

— stability, **499**

Jet, 409

Jolly spring balance, for determination of S.G., 210

Jones ore-sample splitter, 55

K

Kaolin, used in ceramic industry, 561

Kaolinite, 302

— frequency, **499**

— geochemical notes on, **509**

— group, **276, 330**

— identified in soils, **527**

— lattice type of, **525**

— mode of occurrence, **499**

— stability, **499**

Kerosene, dielectric constant of, 129

Kerogen, 413

Ketton stone, 549

Key-samples, 25

Kieselguhr, 403

Kunzite (variety of spodumene, *q.v.*)

— frequency, **499**

— geochemical notes on, **509**

— mode of occurrence, **499**

— stability, **499**

Kyanite, 304

— behaviour to X-rays, **134**

— frequency, **499**

— geochemical notes on, **509**

— identified in soils, **527**

— in Oldhaven beds, **485**

— index mineral, **483**

— indicative of climatic conditions of deposition, **496**

— mode of occurrence, **499**

— stability, **499**

— used in ceramic industry, **561**

L

- Labelling of samples, 16, 23
- Labradorite, 305
 - frequency, 499
 - geochemical notes on, 509
 - identified in soils, 527
 - mode of occurrence, 499
 - stability, 499
- Lake District, granites, 8
 - ore, 406
 - sediments, correlating horizons in, 83
- Lamination, in samples, 34
- Laterite, 384
- Lattice type, of clays, 525
- Lawsonite, 308
 - frequency, 499
 - geochemical notes on, 509
 - mode of occurrence, 499
 - stability, 499
- Lenham beds, Surrey, correlation of outliers of, 488
- Lepidolite, 308
 - frequency, 499
 - geochemical notes on, 510
 - mode of occurrence, 499
 - stability, 499
- Lepidomelane, 307
 - frequency, 499
 - geochemical notes on, 510
 - mode of occurrence, 499
 - stability, 499
- Leucite, identified in soils, 528
- Leucoxene, 308
 - as compound mineral, 186
 - electrical properties of, 127
 - frequency, 499
 - geochemical notes on, 510
 - identified in soils, 528
 - mode of occurrence, 499
 - stability, 499
- Levantian stage, samples from, 481
- Lewisian gneiss, 494
- Lignite, 360, 308
- Limestone, 360, 392
 - base bed, 548
 - carboniferous, 544, 545
 - dolomitic, 360, 395
 - extraction of heavy minerals from, 471
 - Freestone, 548
 - for cement manufacture, 557
 - Lincolnshire, 549
 - magnesian, 549
 - oolitic, 360, 397, 548
 - Perryvot, 548
 - pisolitic, 360, 397
 - Portland, 548
 - trade name for, 574
 - Whitbed, 548

- Limonite, 309
 - electrical properties of, 127
 - frequency, 499
 - geochemical notes on, 510
 - identified in soils, 527
 - mode of occurrence, 499
 - stability, 499
- Lithologic planes, transgression of time-planes by, 469
- Lithology, definition of, 1
- London basin, Pliocene history of, 8
- London and Home Counties, sediments in, 6
- Los Angeles, samples from, 479
- Lustre, 223
- "Lustre-mottling," 369

M

- Macroscopic examination of samples, 31, 62
- Madagascar, rare earth bearing sands of, 9
- Mæotic stage, samples from, 482
- Magnesian limestone, of Mansfield district, 549
- Magnesite, 309
 - for cement manufacture, 557
 - frequency, 499
 - geochemical notes on, 510
 - mode of occurrence, 499
 - stability, 499
 - used in ceramic industry, 561
- Magnetic properties of minerals, 126, 223 (see also under individual minerals)
 - separation of heavy minerals, 121
- Magnetite, 310
 - behaviour to X-rays, 134
 - dielectric constant of, 129
 - electrical properties of, 127
 - frequency, 499
 - geochemical notes on, 510
 - identified in soils, 527
 - magnetic properties of, 126
 - mode of occurrence, 499
 - stability, 499
- Magnets, electro-, 123
 - horseshoe, 122
- Malachite, identified in soils, 528
 - in coal, 78
- Manaccanite, 301
- "Manjak," 415
- Marcasite, 311
 - electrical properties of, 127
 - frequency, 499
 - geochemical notes on, 510
 - identified in soils, 528
 - magnetic properties of, 126
 - mode of occurrence, 499
 - stability, 499

- Marine conditions, of sedimentation,** 436
Marl, 360, 388
 — for cement manufacture, 557
Mastic asphalt, 541
Mayntz Petersen "Flourometer," 105
Mechanical analysis of sediments, 82
 — centrifugal methods, 108
 — elutriation, 95
 — pipette method, 107
 — sedimentation, 105
 — sieving, 85
Mechanical origin, of rocks, 361
 — stage, rotating, for grain counting, 155
Medicine, sedimentary petrography applied to, 578
Mega sample splitter, 55
Megascopic (macroscopic) examination of samples, 31
Melanite, 312
 — frequency, 499
 — geochemical notes on, 510
 — mode of occurrence, 499
 — stability, 499
 "Melborne rock," 400
Mercuric potassium iodide, use with centrifuge for heavy mineral separation, 69
Metahalloysite, lattice type of, 525
Metal grinding, silicosis scheme, 585
Meteorograms, 6
Methyl alcohol, dielectric constant of, 129
Methylated spirit, for washing heavy mineral residues, 52
Methylene iodide, method of determining S.G., 211
Methylethylketone, as a mountant, 42
 "Meyer sand," 479
Mica, dielectric constant of, 129
Mica group, 253, 285, 307, 316, 324
Mica-quartz, identification of, 186
Micro-chemical analysis, 147
 — quantitative methods of, 148
 — qualitative methods of, 150
 — sampling for, 151
 — spot tests, 150
 — volumetric methods of, 149
Microcline, 313
 — evidence of humid environment of sedimentation, 498
 — frequency, 499
 — geochemical notes on, 510
 — identified in soils, 527
 — mode of occurrence, 499
 — stability, 499
Micrometer, eve-piece, 160
 — stage, 161, 199
Micrometric analysis, 198
Micro-organisms, mount for, 57
 — simultaneous separation of, 58
 — single separation of, 48
 — treatment of incoherent rocks for recovery of, 48
Micropertthite, identified in soils, 528
Microscope, comparison, 564
 — document, 564
 — lamp, 159
 — petrological, 152
 — slides, preparation of 35, 442
 — stereoscopic binocular, 155, 564
Microscopical examination of rock minerals, 155, 442
 — sediments, 152, 442
 — special equipment for, 153
 "Microsplit," 55
Micro-splitter, 56
Mid-Continent oilfield, samples from, 483
Midlands, palaeozoic sediments of, 8
Millerite, in coal, 78
Millstone grit, climatic conditions at deposition of, 496
 — of Yorkshire, 7, 492
 — monazite in, 494
Mineral aggregates, identification under microscope, 185
 — origin, 493
 — suites, 491
Minerals, correlation of, 464
 — determination of sign of, 172
 — found in soils, 525
 — frequency, 498, 499
 — lateral persistence of, 462
 — masked by alteration products, 188
 — mode of occurrence, 498, 499
 — stability, 499
 — vertical range of, 463
Mispickel, identified in soils, 528
Moh's scale, of hardness, 216, 605
Moine series, 494
Moisture content (hygroscopic), of sediments, 199
 — of impregnated rocks, 199
Molybdenite, identified in soils, 528
 — in coal, 78
Monazite, 314
 — frequency, 499
 — geochemical notes on, 510
 — identified in soils, 528
 — in millstone grit of Yorkshire, 494
 — in Scottish granite, 494
 — magnetic properties of, 126
 — mode of occurrence, 499
 — stability, 499
Monoclinic system, 222, 227, 603

- Montmorillonite, 315**
 — frequency, 499
 — geochemical notes on, 510
 — lattice type of, 525
 — mode of occurrence, 499
 — stability, 499
- Montmorillonite-Beidellite Series, 251, 315, 318**
 "Moor" grit, 369
 Moreni district, Rumania, samples from, 481, 482
 "Mosaic" breccias, 364
Mountants for thin sections, air, 41, 57
 — — — Canada balsam, 40
 — — — gelatine solution, 42
 — — — methylethylketone, 42
 — — — rubber dissolved in xylene, 42
 — — — synthetic resin, 42
 — — — temporary, 42
 — — — wax, 42
- Mounting of sand grains, cedar oil for, 56**
 — — — for microscopical examination, 56
- "Morphology," grain, 448**
 Mud, for cement manufacture, 557
Mudstone, 360, 388
 — trade name for, 574
- Mullite, used in ceramic industry, 561**
Muscovite, 316
 — frequency, 499
 — geochemical notes on, 510
 — identified in soils, 527
 — magnetic properties of, 126
 — mode of occurrence, 499
 — stability, 499
- N**
- Nacrite, lattice type of, 525**
 Native asphalts, heavy minerals of, 546
Natural rock asphalt, 543
 — — — differentiation between synthetic and, 546
- Nepheline-Syenite, 561**
Nephrite, 318
 — frequency, 499
 — geochemical notes on, 511
 — mode of occurrence, 499
 — stability, 499
- New Red Sandstone, of the West of England, 5**
Nitrates, 361, 430
Nitratine, 430
Nitrobenzene, dielectric constant of, 129
Nontronite, 318
 — frequency, 499
 — geochemical notes on, 511
 — mode of occurrence, 499

- Nontronite, stability, 499**
 — lattice type of, 525

O

- Octahedrite, 235**
Oil-buoyancy methods of mineral concentration, 131
Oil-sand, comprehensive analysis of producing, 480
 — correlation by investigation of physical properties of minerals, 483
 — stratigraphical differentiation of, 479
 — stratigraphical identity of producing, 482
- Oil shale, 360, 413**
Oilfield sample-container, 22
 — samples, 24
 — — — determination of permeability of, 200
 — stratigraphy, petrographical differentiation of "stages" and formations, 481
- Old Red Sandstone, used as building stone, 548**
Oldhaven Sands, 485
Oligoclase, 318
 — frequency, 499
 — geochemical notes on, 511
 — identified in soils, 527
 — mode of occurrence, 699
 — stability, 499
- Olivine, 319**
 — frequency, 499
 — geochemical notes on, 511
 — group, 284, 319
 — identified in soils, 527
 — index mineral, 491
 — magnetic properties of, 126
 — mode of occurrence, 499
 — stability, 499
- Omphacite (variety of diopside, *q.v.*)**
 — frequency, 499
 — geochemical notes on, 511
 — mode of occurrence, 499
 — stability, 499
- "Onyx marble," 421**
Oolitic and pisolitic limestone, 360, 397
Ooze, abyssal, 360, 398, 402
 — globigerina, 399
 — pteropod, 399
- Opal, 320**
 — behaviour to X-rays, 134
 — frequency, 499
 — geochemical notes on, 511
 — mode of occurrence, 499
 — stability, 499
- Optic axial angle, determination of,**

- Optical properties of minerals, 223, 448**
 (see also under individual minerals)
 ——— anomalous (see under individual minerals)
 ——— summary of, 184
 ——— sign, minerals arranged in order of, 614
- Organic origin, rocks of, 390**
 — remains, in samples as aid to diagnosis, 34, 495
- Origin, source of, of minerals, 493**
- Orthite, 232**
 — geochemical notes on, 500
- Orthoclase, 321**
 — frequency, 499
 — geochemical notes on, 511
 — identified in soils, 527
 — mode of occurrence, 499
 — stability, 499
- Orthorhombic system, 221, 226, 603**
- Ottrelite, 323**
 — frequency, 499
 — geochemical notes on, 511
 — mode of occurrence, 499
 — stability, 499
- Outliers, correlation of, 488**
- P**
- Palaeogeography, bearing of sedimentary petrography on, 2, 480**
- Palaeogeographical restoration, 405**
- Palaeozoic sediments, of the Midlands, 8**
- Palagonite, identified in soils, 528**
- Panning, 65**
 — influence on mineral counts, 451
- Paragenesis, 491**
- Parent-rock, relation of sediment to, 434**
- Particle shape, 117**
 — microscope for determination of, 158
 — size, classification of, 96
 — microscopical measurement of, 114, 158
 — recording of average, 114
- "Pea Grit," 369, 397, 398**
- Pearls, fluorescence of, 145**
- Pebble, definition of, 555**
- Pegmatite, 561**
- Pendle slate bed, 550**
- Pennant sandstone, of Bristol district, 549**
- Penninite, 323**
 — frequency, 499
 — geochemical notes on, 511
 — mode of occurrence, 499
 — stability, 499
- Periclase, 324**
 — frequency, 499
 — geochemical notes on, 511
 — mode of occurrence, 499
 — stability, 499
- Permeability, determination of, 200**
 — measurement of, 202
- Perrycot limestone, 548**
- Persistence diagram, of minerals, 462**
- Perthite, 322**
- Perthitic intergrowths, of feldspar, 187**
- Petrogenesis, 1**
- Petroleum geology, influence of evolution of sedimentary petrography on, 3**
- Petrological microscope, 152**
 — spectroscope for, 163
 — stereoscopic binocular, 155
 — stereoscopic binocular, notes on use of, 157
- Phenyl-di-iodoarsine, as refractive index liquid, 183**
- Phlogopite, 324**
 — frequency, 499
 — geochemical notes on, 511
 — identified in soils, 527
 — mode of occurrence, 499
 — stability, 499
- Phosphatic rocks, 360, 417**
- Phosphorescence spectra, 142**
- Phosphorite (see Apatite)**
- Photomicrographs, for presentation of evidence, 566**
 — of ceramic bodies, 562
- Physical features, of minerals, 445**
- Picotite, 325**
 — electrical properties of, 127
 — frequency, 499
 — geochemical notes on, 511
 — magnetic properties of, 126
 — mode of occurrence, 499
 — stability, 499
- Piedmontite, 326**
 — frequency, 499
 — geochemical notes on, 511
 — identified in soils, 527
 — mode of occurrence, 499
 — stability, 499
- Pinite, 188**
- Pipette method, of particle size classification, 107**
 — particle size classification of soils, 531
- Pisolithic limestone, 360, 397**
- Pistacite, 282**
- Plagioclase feldspar, 327**
 — group, 231, 238, 241, 257, 305, 318
- Pleochroism, 224 (see also under individual minerals)**
- Pleonaste, 260**
 — identified in soils, 528

Pliocene, of London basin, 8
 — of Cornwall, 494, 497
Plutonic outcrops, correlated by accessory minerals, 476
Pocket clay, 384
Polarising apparatus, for determination of thickness of rock sections, 48
Polish oilfields, samples from, 483
Pollen flora, fixing age of sediments by, 83
Porosity, determination of, 203
 — relationship between specific gravity and, 204
Porous rocks, synthetic resin impregnation of, 42
Portland cement clinker, 558
 — limestones, 548
Pozzolana, 557
Pozzuoli, 557
Prism spectrometer, 139
Peat, 360, 407
Provenance, 432
 — investigations of, 492
Province, distributive, 432, 436, 437, 490, 495
Psilomelane, 327
 — frequency, 499
 — geochemical notes on, 511
 — mode of occurrence, 499
 — stability, 499
Pteropod ooze, 399
Pudding stone (Hertfordshire), 363
Pyrite, 327
 — attached to chert, 186
 — electrical properties of, 127
 — elimination from heavy residues, 75
 — frequency, 499
 — geochemical notes on, 512
 — identified in soils, 528
 — mode of occurrence, 499
 — stability, 499
Pyro-electricity, method of detecting, in crystals, 148
Pyrolusite, 328
 — electrical properties of, 127
 — elimination from heavy residues, 76
 — frequency, 499
 — geochemical notes on, 512
 — magnetic properties of, 126
 — mode of occurrence, 499
 — stability, 499
Pyrope, 329
 — frequency, 499
 — geochemical notes on, 512
 — mode of occurrence, 499
 — stability, 499
Pyrophyllite, 330

Pyrophyllite, frequency, 499
 — geochemical notes on, 512
 — identified in soils, 527
 — lattice type of, 525
 — mode of occurrence, 499
 — stability, 499
 — used in ceramic industry, 561
Pyroxene, identified in soils, 528
 — group, 230, 246, 277, 281, 299, 340
Pyrrhotite, 330
 — electrical properties of, 127
 — elimination from heavy residues, 76
 — frequency, 499
 — geochemical notes on, 512
 — identified in soils, 528
 — magnetic properties of, 126
 — mode of occurrence, 499
 — stability, 499

Q

Quarterming, 27
Quartz, 331
 — behaviour to X-rays, 134
 — dielectric constant of, 129
 — fluorescence of, 144
 — frequency, 499
 — geochemical notes on, 512
 — identified in soils, 527
 — in limestone, 546
 — mode of occurrence, 499
 — stability, 499
 — used in ceramic industry, 561
 — wedge, 164
Quartzite, 360, 370
 — trade name for, 574

R

R.U. powder, for spectrum analysis, 140
Radiolarian earth, 403
Radium, in coal, 79
Reciprocal relationship, between mineral species, 458
Refractive index 166 (see also under individual minerals)
 — Becke's white line method of determination of, 166
 — diagnosis of minerals by, 170
 — liquids, 182
 — storage of, 183
 — minerals arranged in order of, 611
 — of immersion media, 182
 — Schroeder van der Kolk's method of determination of, 180
Refractories industry silicosis scheme, 582
 — sedimentary petrography applied to, 589

- "Regolith," 517
 Residual clay, 360, 384
 Retardation and vibration directions, 171
 Rhombohedral system (tetragonal), 220, 228, 603
 Riebeckite, 333
 — frequency, 499
 — geochemical notes on, 512
 — mode of occurrence, 499
 — stability, 499
 Rillonite, 316
 "Roach," 548
 Rock fragments, identification of, 185
 — minerals (see also under individual minerals)
 — — characters in sediments, 224
 — — chemical composition of, 216
 — — cleavage, 216
 — — diagnostic properties of, 215
 — — fracture, 216
 — — habit, 216
 — — hardness, 216
 — — microscopical examination of, 185
 — — optical properties of, 184
 — — structure, 216
 — — systems of crystallisation, 216
 — particles, classification of, 85
 — — roundness, 119
 — — sphericity, 119
 — — surface area of, 119
 — salt, 3
 — — dielectric constant of, 129
 — — sections, thickness of, 47
 Rotary sample splitter, 55
 Rounding of grains, 5
 Roundness of rock particles, 119
 Rubber, dissolved in xylene, as a mountant, 42
 Rubble, definition of, 555
 — breccia, 364
 Ruby (variety of corundum, *q.v.*)
 — frequency, 499
 — geochemical notes on, 513
 — identification by fluorescence, 144
 — mode of occurrence, 499
 — stability, 499
 Rudaceous rocks, 360, 362
 Rumanian oilfields, palaeontological stages and sub-divisions of tertiary sequence, 481
 Rutile, 333
 — behaviour to X-rays, 134
 — dielectric constant of, 129
 — electrical properties of, 127
 — frequency, 499
 — geochemical notes on, 513
 — identified in soils, 527
 — in Oldhaven beds, 485
 Rutile, mode of occurrence, 499
 — needles in clays, 4
 — stability, 499
- S**
- Sagenite, 334
 Saline rocks, 361, 426
 — — extraction of heavy minerals from, 472
 Sample bags, labelling of, 24
 — boxes, labelling of, 24
 — container, oilfield, 22
 — indexing, 25
 — splitter, Jones, 55
 — — mega-, 55
 — — micro-, 56
 — — rotary, 55
 Sampling, 15
 — coning, 29
 — consolidated sediments, 17
 — incoherent material, 16
 — in vertical sections, 15
 — oilfield, 16
 — plastic materials, 16
 — quartering, 27
 — subsurface, 15, 16
 — surface, 15, 16
 — of bituminous road mixtures, 575
 Samples, auger-drill, 17
 — bailer, 78
 — bit, 18
 — cable-tool, 18
 — core, 16, 19
 — drying, 31
 — Fauck system, 21
 — incoherent material, 16
 — indexing of, 25
 — key, 25
 — labelling of, 16, 23
 — permanent storage of, 23, 24
 — special structures of 34
 Sand, coarse, limiting dimensions of, 85, 555
 — fine, limiting dimensions of, 85, 555
 — mounting for microscopical examination, 56
 — rounding of grains, 5
 — definition of, 555
 Sands, Cambridgeshire, 6
 — cohesiveness test of, 196
 — for glass making, 3
 — for filtration purposes, 597
 Sandstone, 360, 366
 — Pennant, 549
 — trade name for, 574
 — industry silicosis scheme, 530
 Sanidine (variety of orthoclase feldspar, *q.v.*)
 — frequency, 499
 — geochemical notes on, 513

- Sanidine**, identified in soils, 528
 — mode of occurrence, 499
 — stability, 499
- Santa Fe springs oilfield**, samples from, 479
- Santorin earth**, 557
- Sapphire** (variety of corundum, *q.v.*)
 — fluorescence of, 145
 — frequency, 499
 — geochemical notes on, 513
 — mode of occurrence, 499
 — stability, 499
- Sapropel**, 412
- Sarmatian stage**, samples from, 482
- Sarsens**, 367
- Schiller-spath**, 282, 300
- "Sedimentary mineralogy,"** 7
- Sedimentary petrography**, bearing on palaeogeographical problems, 490
 — definition of, 1
 — evolution of, 2
 — in Belgium, 9
 — Europe, 9
 — France, 9
 — Germany, 10
 — Holland, 10
 — Italy, 10
 — Switzerland, 10
 — United States, 11
 — function of, in soil investigations, 515, 534
 — influence of industry on, 13
 — rocks, classification of, 360
 — definition of, 1
 — testing of, 191
- Sedimentation**, 105
 — centrifugal methods of, 105
 — cycle of, 431
 — for particle size classification, 108
 — marine conditions of, 436
 — method, of soil analysis, 530
 — of soil particles, 529
- Sediments**, classification of, 6
 — colour of, 32
 — consolidated, 358
 — correlation of, 431
 — differentiation of, 435
 — mechanical analysis of, 82
 — microscopical examination of, 152
 — moisture content of, 199
 — relation of parent rock to, 434
- Selenite**, 293
 — geochemical notes on, 513
 — plate, 163
- Separation of heavy minerals** (see concentration of heavy minerals)
- Sericite**, identified in soils, 527
- Serpentine**, 335
 — geochemical notes on, 513
 — identified in soils, 527
- Seyssel asphalt**, 542
- Shale**, 360, 388
 — calcareous, 360, 389
 — trade name for, 574
 — Shape of rock particles, 117
 — "Sheffield ganister," 371
 — Shelly limestone, 394
 — Shimmer aggregates, 187
 — Shingle, definition of, 556
 — Siderite, 336
 — frequency, 499
 — geochemical notes on, 513
 — identified in soils, 528
 — mode of occurrence, 499
 — stability, 499
- Sieve analysis**, 84, 85, 88
 — British standard sieves, 86, 88
 — expression of results, 91
 — graphical, 92
 — Institute of Mining and Metallurgy screens, 86, 88
 — technique of, 89
 — Tyler sieves, 86, 88
 — United States standard sieves (A.S.T.M.), 86, 88
- Sign of minerals**, determination of, 172
 — uniaxial, 172
 — biaxial, 175
- Silica**, determination of total, 583
 — free, 581, 583
 — rock, 3
- Siliceous earth**, 360, 403
 — rocks, 360, 361, 400, 425
 — sinter, 361, 426
- Silicosis**, 578
 — Asbestos industry scheme, 585
 — Metal grinding industry scheme, 582
 — Refractories industry scheme, 582
 — Sandstone industry scheme, 580
 — theories of cause of, 585
- Sillimanite**, 336
 — frequency, 499
 — geochemical notes on, 513
 — identified in soils, 527
 — index mineral, 492
 — mode of occurrence, 499
 — stability, 499
 — used in ceramic industry, 561
- Silt**, limiting dimensions of, 85
 — definition of, 556
- Siltstone**, 360, 373
- Silver**, in carbonaceous shale, 78
- "Sira" wax**, as a mountant, 42
- Slags**, fluorescence of, 144
- Slate**, Cotteswold, 550
 — detrital minerals of, 5
 — Flagstones, 550
 — Stonesfield, 550
 — Tilestones, 550
 — trade name for, 574
 — use as building material, 549
- Soil**, analysis, 522

Soil, application of sedimentary petro-
graphy to study of, 515, 534
— bibliography, 536
— classification, 518
— colouring, 532
— constitution, 523
— — mechanical, 529
— particles, dispersion of, 530
— sedimentation of, 529
Sollas diffusion column, method of de-
termining S.G., 211
Soluble bitumen, determination of, 195
Specific gravity, 200
— — apparent, 204, 206
— — displacement method, 209
— — hydrostatic method, 209
— — Jolly spring balance method,
210
— — minerals arranged in order
of, 607
— — of loose sediments, 208
— — relationship between poros-
ity and, 204
— — Sollas diffusion column
(methylene iodide method), 211
— — true, 206
— — Walker steel-yard balance,
211
— — Westphal balance method,
211
Spectrograms, 140
Spectrograph, Hilger automatic quartz-
glass, 142
Spectrometer, prism, 139
— X-ray, 136
Spectroscope, for petrological micro-
scope, 163
Spectrum analysis, 138
— — absorption spectra method,
142
— — carbon arc cathode layer,
141
— — fluorescence (ultra-violet)
method, 142
— — phosphorescence spectra
method, 142
— — X-ray, 137
Spessartite, 338
— frequency, 499
— geochemical notes on, 513
— mode of occurrence, 499
— stability, 499
Sphaerosiderite, 424
Sphalerite, 338
— electrical properties of, 127
— frequency, 499
— geochemical notes on, 513
— identified in soils, 528
— in coal, 78
— magnetic properties of, 126
— mode of occurrence, 499
— stability, 499

Sphene (see titanite)
— frequency, 499
— geochemical notes on, 513
— mode of occurrence, 499
— stability, 499
Sphericity of rock particles, 119
Spherulitic structure, 211
Spinel, 330
— behaviour to X-rays, 134
— frequency, 499
— geochemical notes on, 513
— group, 260, 266, 296, 325, 339
— mode of occurrence, 499
— stability, 499
Spodumene, 340
— frequency, 499
— geochemical notes on, 513
— mode of occurrence, 499
— stability, 499
— used in ceramic industry, 561
"Spot" tests, 150
Stability, of minerals, 498, 499
Stage micrometer, 161, 199
"Stages" and formations, petrogra-
phical differentiation of, 481, 491
Stalactites, 421
Stalagmites, 421
Staurolite, 341
— frequency, 499
— geochemical notes, on, 514
— identified in soils, 527, 528
— indicative of climatic conditions
of deposition, 497
— in the Bunter pebble beds of
S.W. England, 494
— in the Oldhaven beds, 487
— in the Pliocene deposits of Corn-
wall, 497
— magnetic properties, of, 126
— mode of occurrence, 499
— stability, 499
— in shimmer aggregates, 187
Steatite, 343
— frequency, 499
— geochemical notes on, 514
— mode of occurrence, 499
— stability, 499
— lattice type of, 525
— used in ceramic industry, 561
Stoke's law, application to elutriation,
96
— — to soil analysis, 531
Stonesfield slate, 550
Storage of samples, 23, 24
Stratigraphical differentiation, of oil-
sand, 470
— — of field outcrops, 485
— — identity, of producing oil-sand,
482
Strontianite, 344
— fluorescence of, 144
— frequency, 499

- Strontianite, geochemical notes on, 514
 — mode of occurrence, 499
 — stability, 499
 Structure, of minerals, 216 (see also under individual minerals)
 Subside method, of soil analysis, 530
 Sulphates, 361, 428
 Sulphur, 344
 — dielectric constant of, 129
 — frequency, 499
 — geochemical notes on, 514
 — mode of occurrence, 499
 — stability, 499
 Surface area of rock particles, 119
 — impregnation, of friable rocks with synthetic resin, 42, 48
 Switzerland, evolution of sedimentary petrography in, 10
 Sylvite, 427
 Synthetic asphalt, 542, 543
 — use of carboniferous limestone in, 544
 — differentiation from natural rock, 546
 — resin, advantages of, compared with Canada balsam, 43
 — impregnation of friable and porous rocks with, 42
 — preparation of, 44

T

- Talc, 343 (see also under Steatite)
 — geochemical notes on, 514
 — used in ceramic industry, 561
 Tasmanite, 413
 Testing sedimentary rocks, methods of, 191
 Tetragonal system, 218, 226, 603
 Textural analysis, 32, 33, 212
 Thickness, of grains, 167
 — of rock sections, 167
 Thin section correlation, of consolidated sediments, 472
 — sections, air mounting of, 41
 — equipment for, 35, 36
 — of friable rocks, 40
 — impregnated rocks, 40
 — preparation of, 35
 — rubber dissolved in xylene as mountant of, 42
 — synthetic resin impregnation of, 42
 — thickness of, 167
 Thorough impregnation, of friable rocks with synthetic resin, 47
 Thoulet's solution, 69
 Thulite (variety of zoisite, *g.v.*)
 — frequency, 499
 — geochemical notes on, 514
 — mode of occurrence, 499
 — stability, 499
 Tilestones, 550

- Tilgate stone, 369
 Time-planes, transgression by lithologic planes, 469
 Tincal, 430
 Tinstone (see Cassiterite)
 Titanite, 345
 — electrical properties of, 127
 — frequency, 499
 — geochemical notes on, 514
 — identified in soils, 527
 — mode of occurrence, 499
 — stability, 499
 Titanium dioxide, used in ceramic industry, 561
 Topaz, 347
 — behaviour to X-rays, 134
 — fluorescence of, 144
 — frequency, 499
 — geochemical notes on, 514
 — identified in soils, 527
 — mode of occurrence, 499
 — stability, 499
 Torbanite, 360, 412
 Torridonian series, 494
 Totternhoe stone, 400
 Tourmaline, 348
 — behaviour to X-rays, 134
 — electrical properties, 127
 — frequency, 499
 — geochemical notes on, 514
 — identified in soils, 527
 — in the Oldhaven beds, 487
 — magnetic properties of, 126
 — mode of occurrence, 499
 — stability, 499
 Trappoid breccias, 365
 Trass, 557
 Travertine, 421
 Tremolite, 340
 — frequency, 499
 — geochemical notes on, 514
 — identified in soils, 528
 — mode of occurrence, 499
 — stability, 499
 Triassic, sandstones of Durham, 8
 — — — Yorkshire, 8
 Triclinic system, 222, 227, 604
 Trigonal system, 220, 226, 603
 Trigonia grit, 369
 Triphane, 340
 Tripoli, 403
 Tunbridge Wells sand, 485
 Turquoise, identified in soils, 528
 Tyler sieves, 86, 88

U

- Ultra-violet fluorescence, 142
 — — — applied to bitumens, 145
 — — — spectra, 142
 Unconformity, plane of, 465
 United States of America, evolution of sedimentary petrography in, 11

Uranium, in "anthracite bitumen,"
79

Uvarovite, 350

- frequency, 499
- geochemical notes on, 514
- mode of occurrence, 499
- stability, 499

V

Vanadium, in coal ash, 78

Veeder counter, 66

Ventura County, California, samples
from, 487

Vertical range of mineral series, 463

Vesuvianite, 351

- frequency, 499
- geochemical notes on, 514
- mode of occurrence, 499
- stability, 499

Vibration directions, 171

Vibratory methods of mineral concentration, 130

Viluite (variety of vesuvianite, idocrase, *q.v.*)

- frequency, 499
- geochemical notes on, 514
- mode of occurrence, 499
- stability, 499

Vitrain, 410

Vivianite, identified in soils, 528

Voids, 212

Volcanic ash and glass, 528

— clay, 360, 353

— tuff, 557

Volume weight, 212

Vulcanite rings, for mounting large
grains, 57

W

Wadhurst clay, 485

Walker steel-yard balance, for determining S.G., 211

Water absorption, determination of,
213

- analyses of, from Bristol district, 598, 599
- dielectric constant of, 129
- geochemical analyses of, 597
- supplies, sedimentary petrography applied to, 592

Wax mountants, 42

Weald, samples from, 484

Wealden sediments, 7, 486, 492

Weight per cubic foot, determination
of, 212

— — — of coarse aggregates,
212

— — — of fine aggregates, 212

— — — of fillers, 213

Well samples, indexing of, 26

Westphal balance, for determining

S.G., 211

Whitbed limestone, 548

Whiting, used in ceramic industry, 561

Wilcox sand, physical properties of
minerals in, 484

Willemite, fluorescence of, 144

Witherite, fluorescence of, 144

Wolframite, 352

- electrical properties of, 127
- frequency, 499
- geochemical notes on, 514
- identified in soils, 528
- mode of occurrence, 499
- stability, 499

Wollastonite, 352

- fluorescence of, 144
- frequency, 499
- geochemical notes on, 514
- mode of occurrence, 499
- stability, 499

Wygoda sandstone, kyanite as index
mineral of, 483

X

Xenotime, 353

- frequency, 499
- geochemical notes on, 514
- magnetic properties of, 126
- mode of occurrence, 499
- stability, 499

X-rays, 133

- behaviour of minerals to, 134
- crystal analysis, 134
- spectrometer, 136
- spectrum analysis, 137

Y

Yorkshire, Millstone Grit, 7

- sediments, 7
- Triassic sandstones of, 8

Z

Zeolite group, 234

Zinc blende, 358

Zircon, 354

- frequency, 499
- geochemical notes on, 514
- identification by fluorescence, 144
- identified in soils, 527
- in Oldhaven beds, 487
- mode of occurrence, 499
- purple, in Eocene deposits of Cornwall, 494
- — — of Devon, 494
- — — of Dorset, 494
- in Scottish sedimentary rocks, 494
- stability, 499

Zolsite, 356

- frequency, 499
- geochemical notes on, 514
- identified in soils, 527
- mode of occurrence, 499
- stability, 499

AUTHOR INDEX

A

Abraham, H., 417, 547
 Abrams, A. D., 94
 Ahrens, W., 42
 Alexander, L. T., 106
 Allen, V. T., 252, 316, 359, 372, 373
 Alling, H. L., 231, 314, 319, 322
 Allison, V. C., 422
 Alty, S. W., 240, 340
 Anderson, B. W., 137, 183
 Andersson, F., 507
 Andrews, L., 98
 Andrews, W. R., 395
 Anten, J., 9, 252
 Antevs, E., 11
 Applin, E. R., 480
 Arber, E. A. N., 408, 409, 411, 413
 Artini, E., 10, 262, 274, 326
 Ashley, G. H., 84
 Attwooll, A. W., 417, 547

B

Bailey, J. P., 280, 283, 306, 341, 350, 351
 Bailey, T. L., 321, 327, 344
 Bailey, W. S., 288
 Baker, H. A., 94, 95, 98
 Bannister, F. A., 312
 Baren, J. van, 10, 271, 293, 353, 528
 Barlow, A. E., 272
 Barrett, B. H., 300, 357
 Barrois, C., 272
 Barrow, G., 187
 Barton, D. C., 370
 Baskerville, C., 79, 144
 Bauer, M., 275, 386
 Baum, L. A. C., 103
 Bayley, W. S., 295
 Beck, C., 153
 Beck, R., 425
 Becker, H., 10
 Berg, G. A., 129
 Berg, L. S., 84
 Berman, H., 178, 179, 216, 223, 224
 Berthois, L., 9
 Billingham, S. A., 249, 277, 282
 Blackwelder, E., 11
 Blake, J. H., 398
 Blanford, W. T., 496

Bobranski, B., 151
 Bonine, C. A., 316
 Bonney, T. G., 5, 363, 368, 492
 Bosazza, V. L., 590
 Boswell, P. G. H., 3, 6, 7, 12, 76, 85, 89, 97, 225, 229, 231, 234, 236, 237, 244, 245, 246, 253, 255, 256, 258, 259, 261, 262, 263, 264, 266, 267, 268, 272, 278, 280, 282, 283, 289, 290, 296, 300, 305, 308, 310, 311, 317, 320, 321, 322, 325, 326, 327, 329, 330, 331, 332, 334, 335, 337, 340, 343, 346, 348, 349, 355, 368, 419, 445, 457, 459, 464, 470, 489, 494, 502, 503, 505, 506, 514, 530, 553, 554, 555, 556, 572, 591, 592
 Bosworth, T. O., 234, 249, 278, 294, 296, 317, 332, 343, 389, 422
 Botset, H. G., 200
 Bowman, T. S., 240, 333
 Bracewell, S., 52
 Bradley, W. H., 235, 262
 Bragg, W. H., 134, 136
 Bragg, W. L., 134, 136
 Bramlette, M. N., 229, 238, 240, 251, 267, 350
 Brammall, A., 8, 81, 135, 170, 231, 234, 236, 237, 244, 253, 254, 255, 259, 261, 271, 272, 280, 285, 296, 311, 315, 317, 319, 322, 332, 335, 337, 340, 346, 348, 349, 354, 355, 388, 432, 449, 475, 493, 509
 Branner, J. C., 276
 Bray, R. H., 106, 295, 503
 Bréon, R., 272
 Brinckmann, R., 83
 Briscoe, H. V. A., 147
 Broome, D. C., 108, 417, 547
 Broughton, M. N., 380
 Brown, I. C., 67
 Brown, L. S., 308
 Bryan, K., 11
 Buckley, E. R., 375
 Buckman, S. S., 470
 Bulman, O. M. B., 383
 Butcher, C. H., 42
 Butcher, W. H., 398
 Butterfield, J. A., 236, 336, 355
 Buttgenbach, H., 293

C

- Capeder, G., 229
 Carnot, A., 419
 Carroll, D. A., 238, 262, 267, 286, 306,
 314, 319, 322, 528
 Carter, C., 298, 368
 Cathrein, A., 187, 509
 Cattelle, W. R., 275
 Cayeux, L., 9, 240, 368, 395, 397, 400,
 419, 507
 Chalk, L. J., 544, 547
 Chambrier, P. de, 417
 Chamot, E. M., 151
 Chapman, F., 262, 333
 Chatterjee, M., 476
 Chelussi, I., 10, 232, 243, 251, 266,
 271, 276, 277, 290, 306, 333
 Child, R. O., 547
 Chrustchoff, K. V., 355
 Chumley, J., 247
 Clarke, F. W., 289, 315, 408, 409, 412,
 419, 423, 428, 430, 505
 Claypool, C. B., 69
 Clerici, E., 10, 71
 Coffey, G. N., 301
 Coil, F., 308
 Collet, L. W., 10, 11, 383
 Colomba, L., 343
 Colony, R. J., 246, 271, 351, 353
 Combe, A. D., 352
 Comber, N. M., 519
 Conacher, H. R. J., 413, 414
 Cope, T. H., 267, 311
 Cox, A. H., 380
 Cox, E. P., 120
 Crook, T., 6, 98, 127, 237, 259, 285,
 336, 340, 348, 410
 Crook, W., 275
 Cullis, C. G., 422
 Cunningham, J., 79

D

- Daly, R. L., 500
 Damour, A., 276, 343
 Dana, J. D., 224, 405
 Danby, A., 417, 547
 Davies, G. M., 6, 237, 249, 258, 259,
 262, 267, 272, 283, 285, 287, 289,
 294, 295, 315, 328, 329, 331, 332,
 336, 337, 339, 340, 343, 346, 348,
 350, 380, 487
 Davies, G. R., 79, 395
 Davies, R., 238, 244, 249, 285, 314,
 317, 319, 322, 332, 463
 Davis, C. A., 389
 Davis, E. F., 262, 271
 Derby, O. A., 354
 Derry, D. R., 451, 489

- Desch, C. D., 559
 Déverin, L., 10, 231
 Dick, A., 4, 335
 Diller, S. J., 244
 Dines, H. G., 237
 Doelter, D., 134
 Doty, R. J., 196
 Double, I. S., 8, 229, 231, 236, 237,
 242, 244, 253, 255, 261, 262, 263,
 264, 283, 289, 305, 311, 314, 317,
 319, 332, 335, 337, 343, 346, 348,
 350, 400
 Doyen, A., 9
 Driver, H. L., 60
 Drugman, J., 285
 Druif, J. H., 251, 323, 326, 351
 Dryden, A. L., 452
 Dryden, L., 94, 453, 455
 Dunstan, W. R., 352

E

- Eddy, C. E., 138
 Edelman, C. A., 10
 Edmunds, F. H., 237, 395
 Edson, F. C., 284
 Eldridge, G. H., 417
 Ellis, D., 596
 Ellisor, A. E., 480
 Ells, S. E., 417
 Emerson, E. V., 381
 Emich, F., 151
 Emory, T., 275
 Endell, K., 135, 525
 Evans, J. W., 165, 178
 Ewing, C. J., 65

F

- Falconer, J. D., 122
 Fearnside, W. G., 507
 Feigl, F., 151
 Feilman, F. P. C., 483
 Fermor, L. L., 386
 Field, R. M., 363
 Finch, J. W., 275
 Fitch, A. A., 138, 140, 340
 Fischer, G., 373
 Fleet, W. F., 8, 197, 236, 244, 247,
 249, 258, 261, 264, 283, 289, 311,
 314, 317, 322, 342, 450, 451, 458,
 489
 Flett, J. S., 237, 380
 Flower, G. C., 350, 481
 Fowweather, F. S., 587
 Fox, C. S., 386
 Fox, H., 402
 Fraser, F. J., 73, 343
 Fraser, H. J., 202
 Frey, M., 417
 Fry, W. H., 301, 326, 330, 525, 527

G

- Gallagher, E. W., 94, 289
 Gardiner, M. I., 229
 Gardner, W., 94
 Gessner, H., 108
 Ghosh, P. K., 476
 Gill, D. M. C., 263
 Gilligan, A., 7, 237, 249, 271, 314, 315,
 317, 319, 322, 332, 347, 354, 369,
 370, 445, 492, 494, 496
 Glinka, K. D., 520
 Goldman, M. I., 11, 156, 245, 283, 507
 Goldschmidt, V. M., 141
 Goodchild, J. G., 395
 Goodwin, N., 405
 Gossling, F., 237, 261, 263, 337, 340,
 488
 Gough, C. M., 543, 547
 Grabau, A. W., 428, 430
 Grahmann, R., 84
 Grant, J., 143, 145
 Grantham, D. R., 476
 Green, J. F. N., 374
 Greenly, E., 231
 Greenwood, H. W., 249, 278
 Gregory, H. E., 330, 385
 Gregory, J. W., 363, 379, 419
 Grim, R. E., 106, 295, 316, 380, 503
 Grimsley, G. P., 375
 Grout, F. F., 375
 Groves, A. W., 244, 280, 476, 493
 Guinard, M., 62
 Gulliver, G. H., 198
 Guttmann, A., 144

H

- Haberlandt, H., 144
 Hadding, A., 138, 363, 368, 370
 Hahn, F. V. von, 105, 108
 Halbouty, M. T., 252
 Hallimond, A. F., 42, 124, 289, 377,
 419, 424, 507, 513
 Hanna, G. D., 58, 60, 62
 Hanna, M. A., 11
 Harder, E. C., 425
 Hardy, F., 245, 246
 Harker, A., 211, 368, 369, 371
 Harris, G. F., 398
 Harrison, J. B., 405
 Hart, R., 528
 Harwood, H. F., 8, 81, 236, 255, 335,
 354, 355, 475, 509
 Hatch, F. H., 6, 98, 383
 Hawkes, L., 234, 241, 247, 249, 300,
 314, 320
 Hayes, C. W., 507
 Hayward, H. A., 280, 337, 340, 348
 Heard, A., 238, 244, 249, 271, 272, 285,
 314, 317, 319, 322, 332, 395, 463

- Hedberg, H. D., 323, 388
 Heim, A., 241
 Hendricks, S. B., 378, 524
 Henry, N. F. M., 300
 Herdman, W. H., 272
 Hess, F. L., 296
 Hewett, D. F., 253, 384
 Hicks, H., 363
 Hill, J. B., 402
 Hill, W., 253, 389, 400, 402
 Hinde, G. J., 402
 Hirst, P., 43
 Hise, C. R. van, 412
 Hissink, D. J., 106
 Hofmann, U., 135, 525
 Holland, T. H., 386
 Holman, B. W., 128, 132
 Holmes, A., 7, 98, 178, 198, 211, 287,
 374, 413, 556
 Honess, A. P., 316
 Hopkinson, J., 363
 Howard, A. D., 75
 Howard, W. V., 6
 Howe, A., 385
 Howe, J. A., 378, 557
 Hudleston, W. H., 398
 Hume, W. F., 262, 400
 Hutchings, W. M., 5, 249, 379, 388
 Hutton, J. G., 534

I

- Iddings, J. P., 224, 308
 Illing, V. C., 4, 6, 17
 Ingham, F. T., 261, 266, 300

J

- Jennings, D. S., 94
 Johannsen, A., 178
 Jones, W. R., 170, 585, 586
 Joseph, A. F., 106
 Jowett, A., 247, 368
 Judd, J. W., 287, 389, 395, 496
 Jukes-Browne, A. J., 363, 365, 378,
 380, 390, 395, 400, 405, 409, 411

K

- Kalkowsky, E., 260, 293
 Kaufmann, F. J., 231
 Keller, W. D., 276
 Kellett, J. G., 272, 336
 Kerr, P. F., 106, 233, 295, 303, 316,
 380, 384
 Keyes, C. R., 382
 Kindle, E. M., 11
 King, F. H., 208, 593
 King, W. W., 364, 365
 Kinney, S. P., 115
 Kispatich, M., 222, 299

Kiteon, A. E., 275
 Klahn, H., 10, 382
 Klinger, F. E., 10
 Knight, B. H., 574
 Kniker, H. T., 480
 Koch, H. L., 55
 Kolbl, L., 83
 Koto, B., 507
 Krumbein, W. C., 55, 94, 106, 114, 460
 Kuhlmann, C. F., 148
 Kundt, A. A. E. E., 146
 Kunitz, W., 67
 Kunz, G. F., 144
 Kyle, J. J., 79

L

Laby, T. H., 138
 Lacroix, A. F. A., 9
 Ladd, G. E., 375
 Langford, W. G., 262, 272
 Lapparent, J. de, 9, 231
 Larsen, E. S., 178, 179, 183, 184, 216, 223, 224
 Lasne, H., 244
 Latter, M. P., 272, 278, 305, 343
 Lea, F. M., 559
 Lee, H. T., 230
 Leech, J. G. C., 135, 476
 Lees, G. M., 402
 Legge, T., 579
 Leggette, M., 43
 Leighton, M. M., 11
 Leinz, V., 10
 Lewis, H. P., 249, 253, 285, 291, 354
 Lingen, J. van der, 354
 Lloyd, S. J., 79
 Lomas, J., 253, 272, 277
 Lonsdale, J. J., 252
 Loos, H., 251
 Lovely, H. R., 483
 Lucas, A., 564
 Lundqvist, G., 83
 Lutati, F. V., 143

M

MacAlister, D. A., 339
 Macalman, D., 94
 MacGregor, A. M., 275
 Mackie, W., 5, 118, 239, 244, 247, 278, 280, 282, 300, 313, 332, 355, 492, 494, 496, 501
 Maddalena, L., 251
 Mann, A., 62
 Mannkopff, R., 141
 Marbut, C. F., 520
 Marchand, B. de C., 531
 Marr, J. E., 6, 7, 388, 395, 512
 Marsden, R. W., 308
 Marshall, C. E., 85, 108, 113, 135, 378, 524, 525, 534

Martens, J. H. C., 270, 292, 306, 340, 354, 357, 419, 504
 Martin, A. P. G., 147
 Mason, C. W., 151
 McCartney, G. C., 489
 McCaughey, W. J., 330
 McMahon, C. A., 388
 Medlicott, H. B., 496
 Melmore, S., 229, 246, 249, 278, 324
 Menell, F. P., 275
 Merrill, G. P., 381, 517
 Merwin, H. E., 183, 291
 Metz, M. S., 252
 Meunier, S., 353
 Meyer, E., 481
 Michel, H., 144
 Middleton, H. E., 106
 Miers, H., 211
 Milner, H. B., 7, 35, 38, 122, 126, 128, 130, 134, 215, 234, 236, 237, 253, 255, 259, 264, 267, 272, 283, 289, 290, 296, 303, 305, 311, 315, 317, 328, 329, 334, 335, 336, 341, 343, 348, 349, 354, 355, 376, 378, 411, 432, 463, 484, 485, 489, 497
 Mingay, J. C. H., 79
 Miser, H. D., 316, 384
 Mitchell, C. A., 151
 Mitchell, R. L., 140
 Moir, J. R., 263
 Morgan, G., 79
 Morgan, R. J., 417
 Moritz, H., 140
 Mortimore, M. E., 483
 Mourant, A. E., 244
 Müller, H., 10
 Munsell, —, 32
 Murray, J., 247, 383, 384, 399, 403
 Muskat, M., 200

N

Neaverson, E., 231, 236, 266, 272, 290, 294, 300, 317, 340, 346, 347, 357
 Neeb, G. A., 238, 241, 257, 528
 Nevin, C. M., 196
 Newton, E. F., 242, 244, 287, 339, 346, 513
 Nichols, J. B., 108
 Nicou, M. P., 417
 Noll, W., 318
 Nordenskiöld, A. E., 79
 Norton, W. H., 364, 365
 Nutting, P. G., 380

O

Ogilvie, H. M., 422
 Olmstead, L. B., 106
 Orrel, J., 268
 Orton, E., 375

O'Reilly, J. P., 255
 Otto, G. H., 54, 55
 Owen, L., 419

P

Page, S., 247
 Palmer, L. S., 365
 Paréjas, E., 10
 Parliche, C., 144, 281
 Parsons, C. L., 380
 Parsons, L. M., 397
 Part, G. M., 35, 38, 247, 320, 350
 Partington, J. R., 136
 Pauling, L., 135
 Pawlica, W., 230
 Payne, C. J., 183
 Penrose, R. A. F., 430
 Perrott, G. J., 115
 Pettijohn, F. J., 11, 229, 277, 350
 Phillips, F. C., 255
 Pla, J., 10
 Picard, F. K., 132
 Piper, A. M., 11
 Popoff, B., 211
 Porter, J. T., 380
 Posnjak, E., 291
 Postel, A. W., 98
 Potonié, R., 10, 412, 413, 414
 Pregl, F., 151

R

Radley, J. A., 143, 145
 Radziszewski, P., 230, 343
 Raeburn, C., 7, 122, 126, 128, 130,
 134, 215, 234, 259, 267, 272, 302,
 315, 335, 341, 343, 348, 349, 355
 Raistrick, A., 247, 300
 Rao, T. V. M., 271, 386
 Rastall, R. H., 6, 8, 98, 185, 246, 247,
 255, 266, 298, 305, 311, 334, 346,
 354, 357, 369, 383, 400, 475, 516
 Raymond, P. E., 383
 Read, H. H., 271
 Reed, F. R. C., 419
 Reed, R. D., 11, 200, 251, 273, 280,
 283, 306, 321, 341, 350, 351, 370,
 487, 488, 489
 Rees, W. J., 253
 Renard, A. F., 383, 384, 399, 403
 Renick, B. C., 318
 Repossi, E., 326
 Retgers, J. W., 10, 71
 Reynolds, S. H., 365
 Ricciardi, I., 276
 Richardson, W. A., 294, 336, 402, 430
 Richter, K., 84
 Richthofen, F. von, 382
 Rickard, T. A., 78

Ridge, J. D., 229, 277, 350
 Ridgway, R., 32
 Riedl, G., 144
 Ries, H., 196, 233, 288, 295, 375
 Robinson, G. W., 515, 517, 520, 521,
 523, 531, 532
 Robinson, W. O., 330
 Rohrbach, C., 71
 Roller, P. S., 103
 Rose, G., 231
 Ross, C. S., 11, 42, 233, 235, 252, 289,
 295, 303, 316, 375, 378, 384
 Roth, R., 489
 Rubel, A. C., 20
 Rubey, W. W., 106, 388
 Ruedmann, R., 383
 Rungaldier, R., 84
 Russ, W., 418, 419
 Russell, A. S., 43
 Russell, I. C., 382

S

Salmojrighi, F., 10, 290, 301
 Schaffer, R. J., 43, 395
 Schmidt, H., 383
 Schneider, H., 289
 Schroeder, F., 67
 Schroeder Van der Kolk, 180
 Schwarz, R., 509
 Scrivenor, J. B., 311
 Scupin, H., 383
 Searle, A. B., 375
 Seebach, K. von, 235
 Selvig, W. A., 584
 Shaler, N. S., 425
 Shand, S. J., 199
 Shannon, E. V., 232, 252, 316, 330,
 375, 384
 Shannon, W. G., 236, 237, 244, 247,
 253, 258, 268, 272, 278, 283, 292,
 296, 298, 303, 314, 328, 335, 336,
 343, 348, 369, 489
 Shaub, B. M., 590
 Shaw, A., 583
 Sidorenko, M., 245
 Sigmond, A. A. J. de, 521
 Simmons, W. C., 352
 Simon, W. G., 10
 Simpson, B., 244
 Skeats, E. M., 345
 Skeats, E. W., 305, 397
 Skerl, J. G. A., 261, 264, 266, 283, 290,
 300, 305, 311, 314, 315, 319, 328,
 334, 337, 340, 343, 346
 Slocum, A. W., 57
 Slomnicki, J., 481
 Smith, E. A., 345
 Smithsonian, F., 8, 125, 180, 244, 298,
 315, 341, 451, 476, 489

Smythe, J. A., 234, 241, 247, 249, 300, 314, 320
 Snow, O. W., 106
 Sollas, W. J., 371
 Solomon, J. D., 8
 Somers, R. E., 276, 295, 378
 Sonstadt, E., 71
 Sorby, H. C., 4, 395
 Sosman, R. B., 426
 Speight, R., 247
 Spencer, E., 211, 336, 378, 513
 Spencer, L. J., 144, 275
 Sprunk, G. C., 412
 Stadler, H., 98
 Stadnichenko, T., 414
 Stamp, L. D., 470
 Stead, J. E., 255, 339
 Steiger, G., 11
 Stephenson, L. W., 316, 384
 Stone, R. W., 78
 Stopes, M. C., 411
 Strahan, A., 402
 Strock, L. W., 141
 Stuart, A., 230, 234, 247, 250, 253, 258, 259, 262, 264, 267, 269, 272, 277, 278, 281, 283, 296, 298, 300, 305, 311, 322, 331, 332, 335, 340, 346, 348, 351, 352, 357, 411
 Stutzer, O., 10, 78, 419
 Sucharda, E., 151
 Sullivan, J. D., 71
 Sulman, H. L., 131, 132
 Sutton, J. R., 275
 Svedberg, T., 108
 Sweet, J. M., 249
 Sweeting, G. S., 314, 317, 319, 322, 332, 369

T

Tacconi, E., 268, 282, 335, 350
 Tallin, E. J., 40
 Tarr, W. A., 11, 179, 276, 359, 397, 400, 402, 426
 Teall, J. J. H., 4, 313, 319, 322, 332, 370, 386, 398, 402
 Tester, A. C., 58, 119, 120
 Thiel, G. A., 84
 Thiessen, R., 411, 412, 413
 Thomas, E. T., 57
 Thomas, H. H., 5, 6, 188, 229, 236, 237, 244, 249, 253, 255, 259, 260, 264, 268, 271, 285, 294, 296, 304, 314, 317, 334, 335, 337, 339, 342, 343, 346, 347, 349, 354, 355, 371, 372, 445, 494, 513
 Thomas, M. D., 94
 Thoulet, J., 9, 71, 232
 Tickel, F. G., 487
 Toit, A. L. du, 419
 Tomkeieff, S. I., 272, 276, 378

Tornebohm, A. E., 559
 Trask, P. D., 11, 108, 110, 111, 113
 Traxler, R. N., 103
 Trowbridge, A. C., 483
 Turner, A. H., 138
 Tuyl, F. M. van, 397, 398, 423
 Twenhofel, W. H., 11, 359, 363, 368, 383, 397, 402, 414, 419, 422
 Tyler, S. A., 308
 Tyrrell, G. W., 365, 373, 386, 398, 408, 426, 430

U

Udluft, H., 10
 Urbain, P., 378
 Ussher, W. A. E., 390
 Uzielli, G., 276

V

Vassar, H. E., 71
 Vaughan, T. W., 11
 Veatch, A. C., 17
 Vendl, A., 269, 271
 Versey, H. C., 244, 249, 263, 298, 305, 314, 340, 343, 368
 Viglino, A., 229

W

Wadell, H., 119, 120
 Walcker, R., 509
 Walcot, C. D., 364
 Walker, A. R. E., 354
 Walker, F., 320
 Wallace, R. C., 397
 Watkins, C. M., 544, 547
 Watson, T. L., 296
 Watts, W. W., 6, 78, 371, 457
 Weed, W. H., 426
 Wegner, T., 83
 Welch, F., 159
 Wells, A. K., 476, 477
 Wentworth, C. K., 11, 55, 85, 91, 94, 118, 120, 212, 359, 553, 554, 555
 Wethered, E., 262, 395, 397, 398
 Wetzol, W., 10
 Weyland, H., 42
 Wheeler, H. A., 375
 Wheeler, R. V., 411
 Wherry, E. T., 384
 Whitaker, W., 295
 White, D., 411, 414
 Whitworth, H. F., 272
 Wilcockson, W. H., 8, 475
 Wilgins, W. L., 55
 Wilkerson, A. S., 352
 Williams, H., 383

- | | |
|--------------------------------------|--------------------------------------|
| Wilm, D., 135, 525 | Wooldridge, S. W., 8, 236, 237, 244, |
| Wilson, D. M., 193, 547 | 261, 263, 283, 289, 298, 305, 335, |
| Winchell, A. N., 178, 224, 257, 273, | 337, 340, 343, 485, 487 |
| 590 | Workman, M., 300 |
| Winkler, C., 79 | Wrage, W., 83 |
| Wolff, F. von, 67 | Wray, D. A., 324 |
| Wollaston, T. C., 321 | Wright, C. H., 523 |
| Woodford, A. O., 73, 230, 273, 286, | Wright, F. E., 178 |
| 306, 324 | Wychoff, R. D., 200 |
| Woods, H., 34 | |
| Woodward, H. B., 368 | |
| Woolacott, D., 397 | |
| | Z |
| | Zerndt, J., 355 |

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